The Physics of Hearing

Consonance and Harmony in Music and its Physical Foundation

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Disclaimer:

I do not pretend that physics or physiology can ``explain'' the beauty and magic of music

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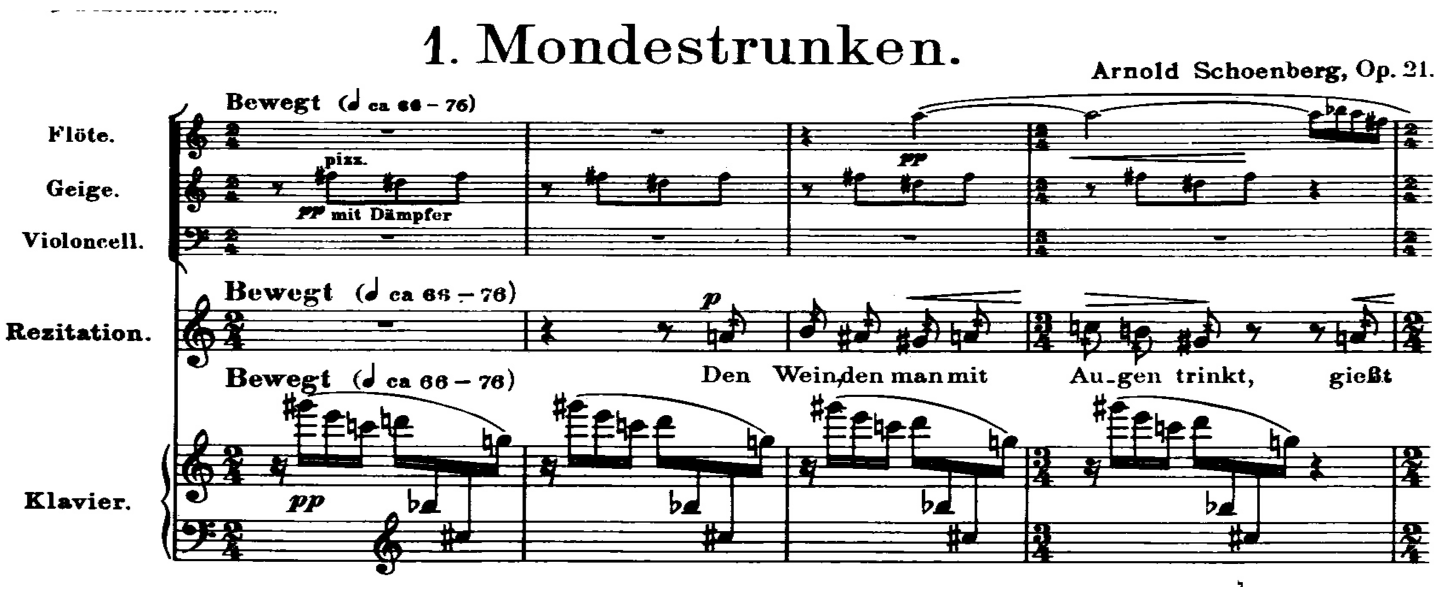
but:

Perhaps it is not justified to derive from one of the components, for instance the tone alone, everything what makes the physics of harmony. But some peculiarities might be learned from it.

Arnold Schönberg, Harmonielehre 1911



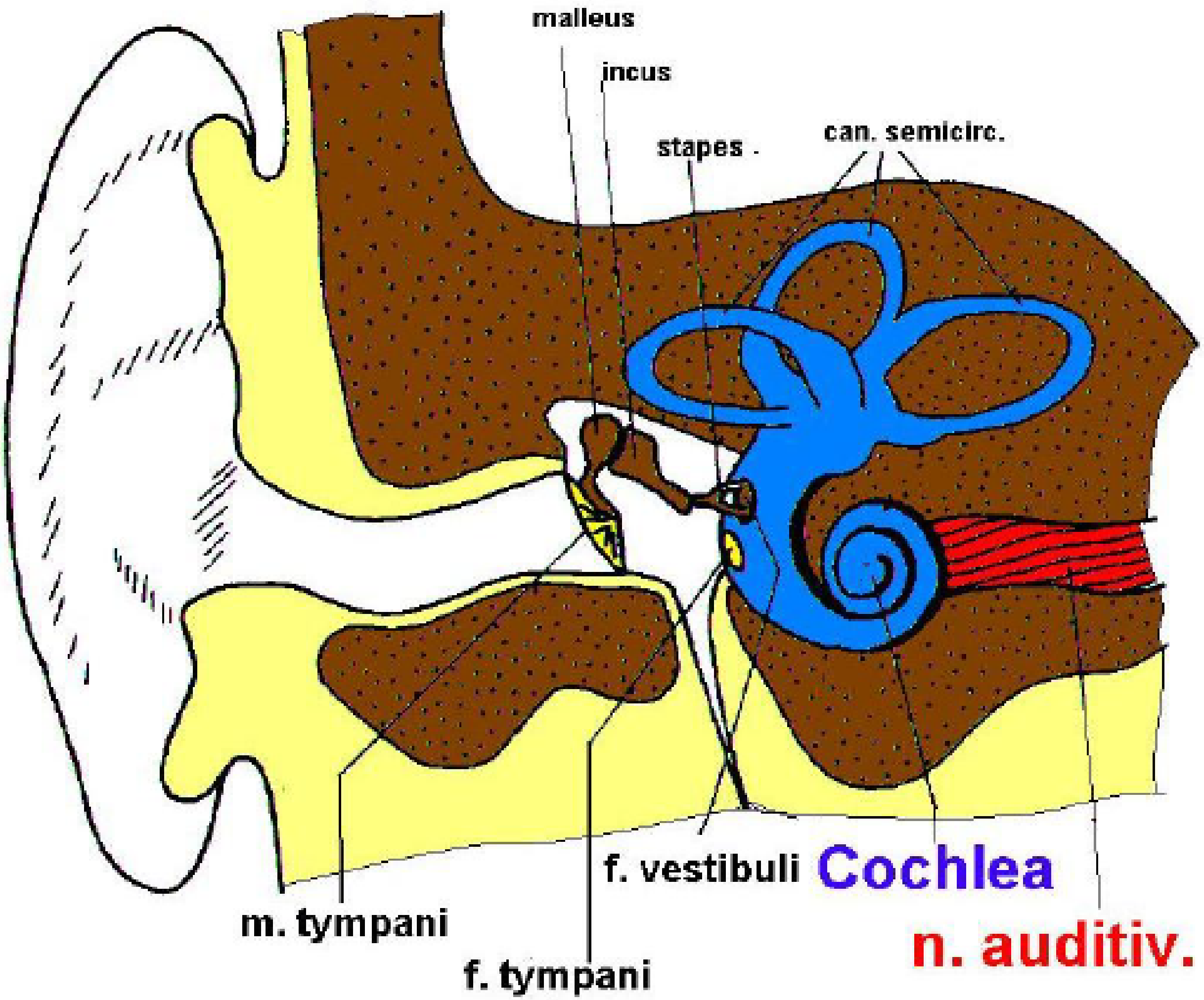
1) Anatomy and Function of the ear

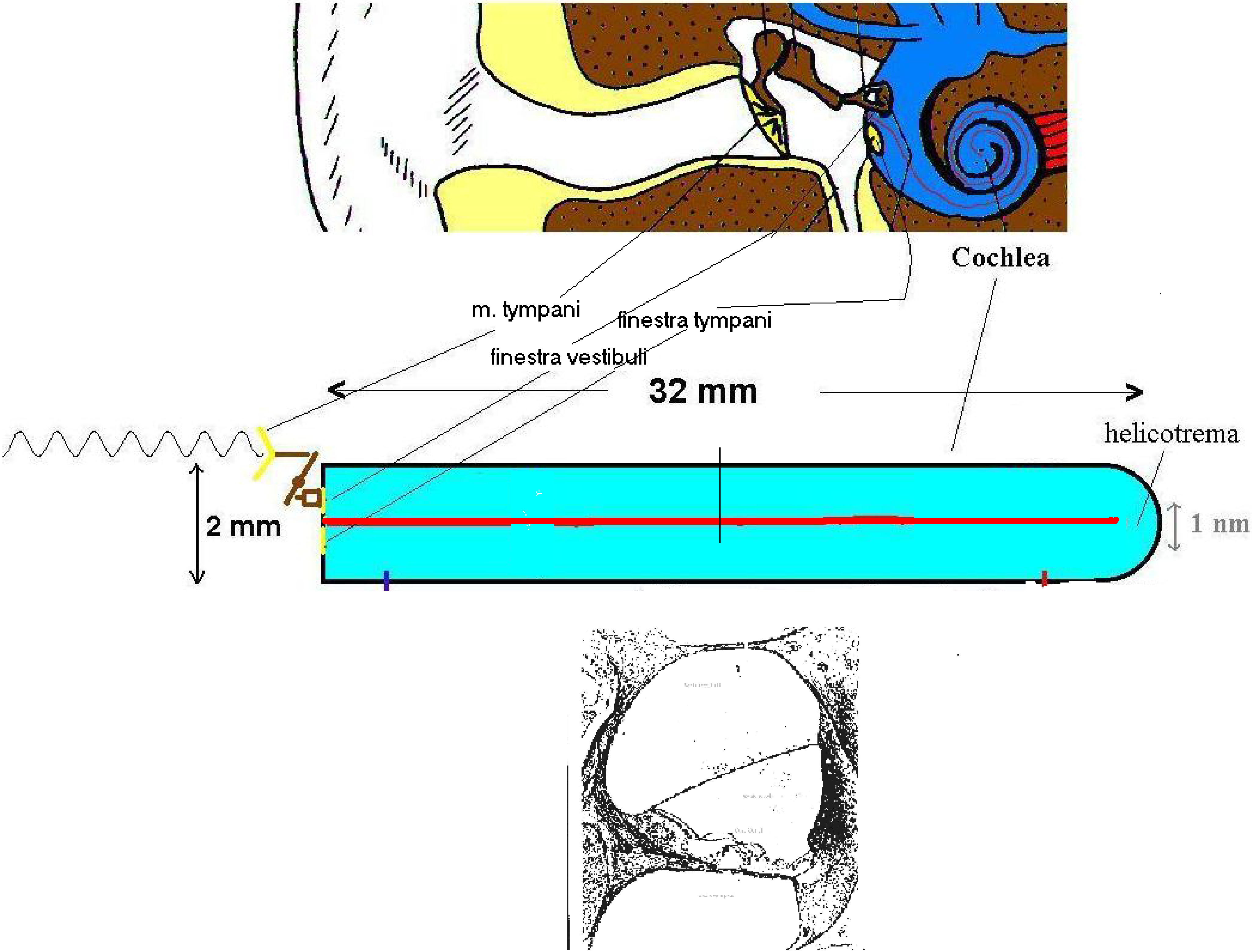
2) From the ear to the brain

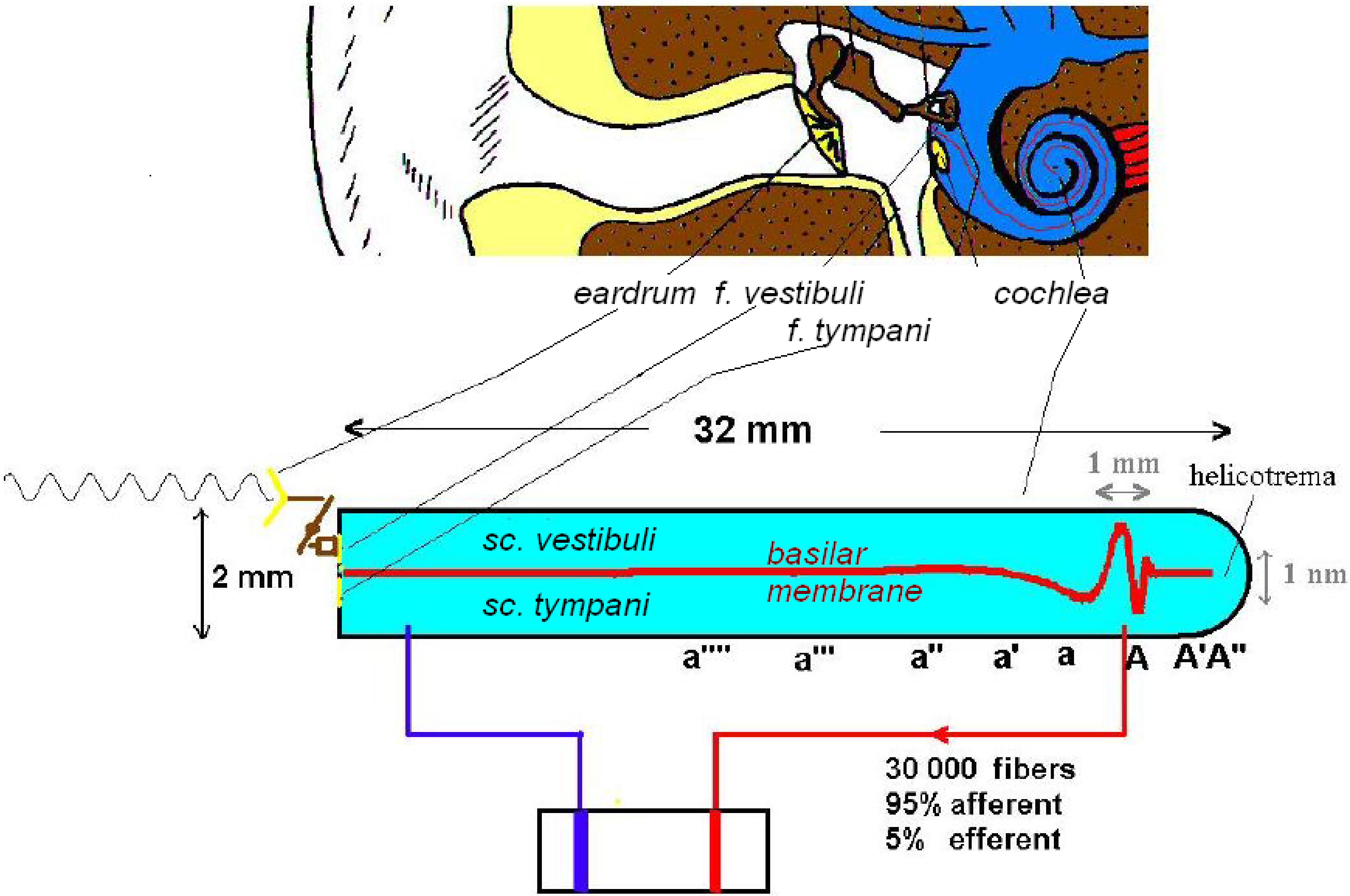
3) The critical bandwidth and the physiological foundation of dissonance and consonance

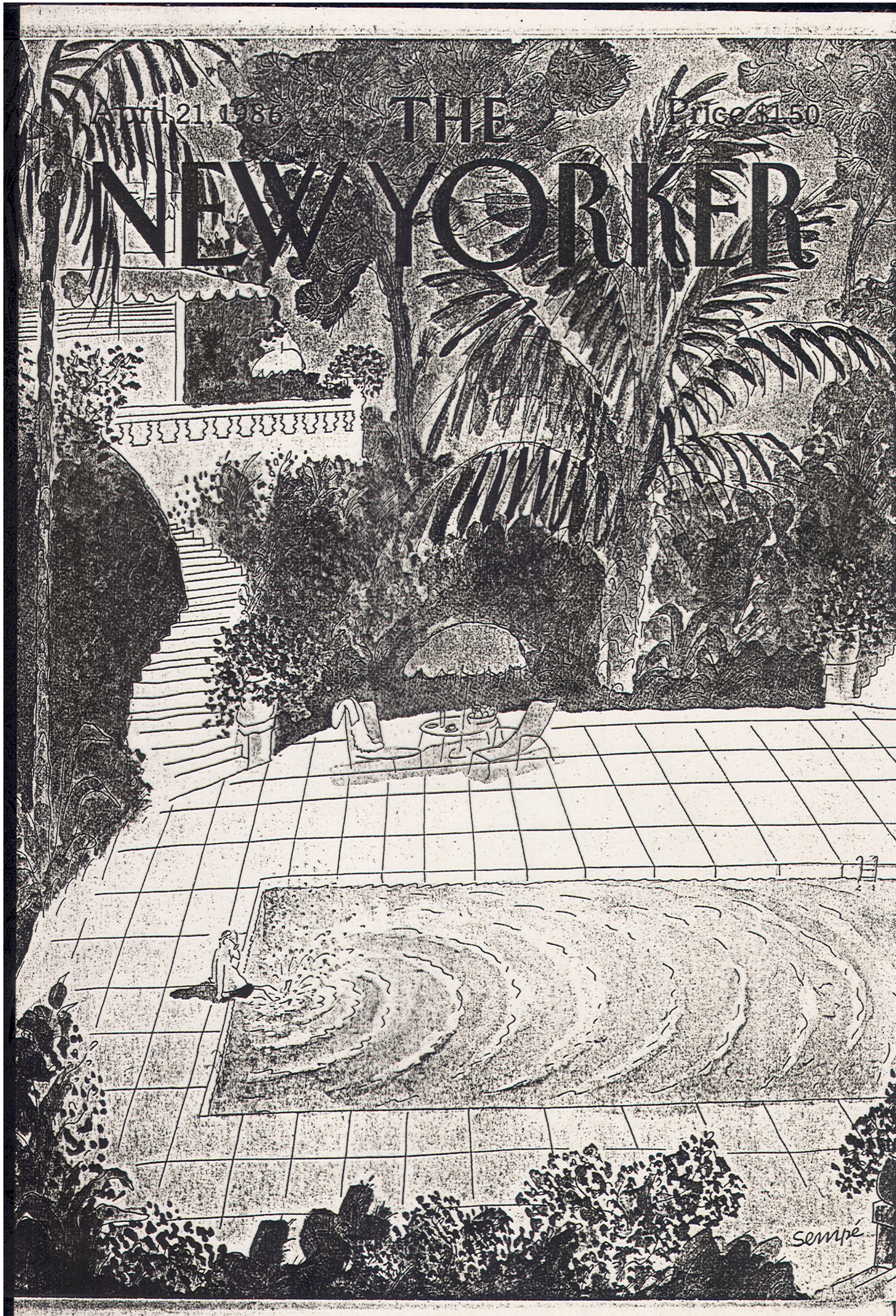
6) Fusion of harmonic tones. Rameau's theory of harmony
Basse fondamentale

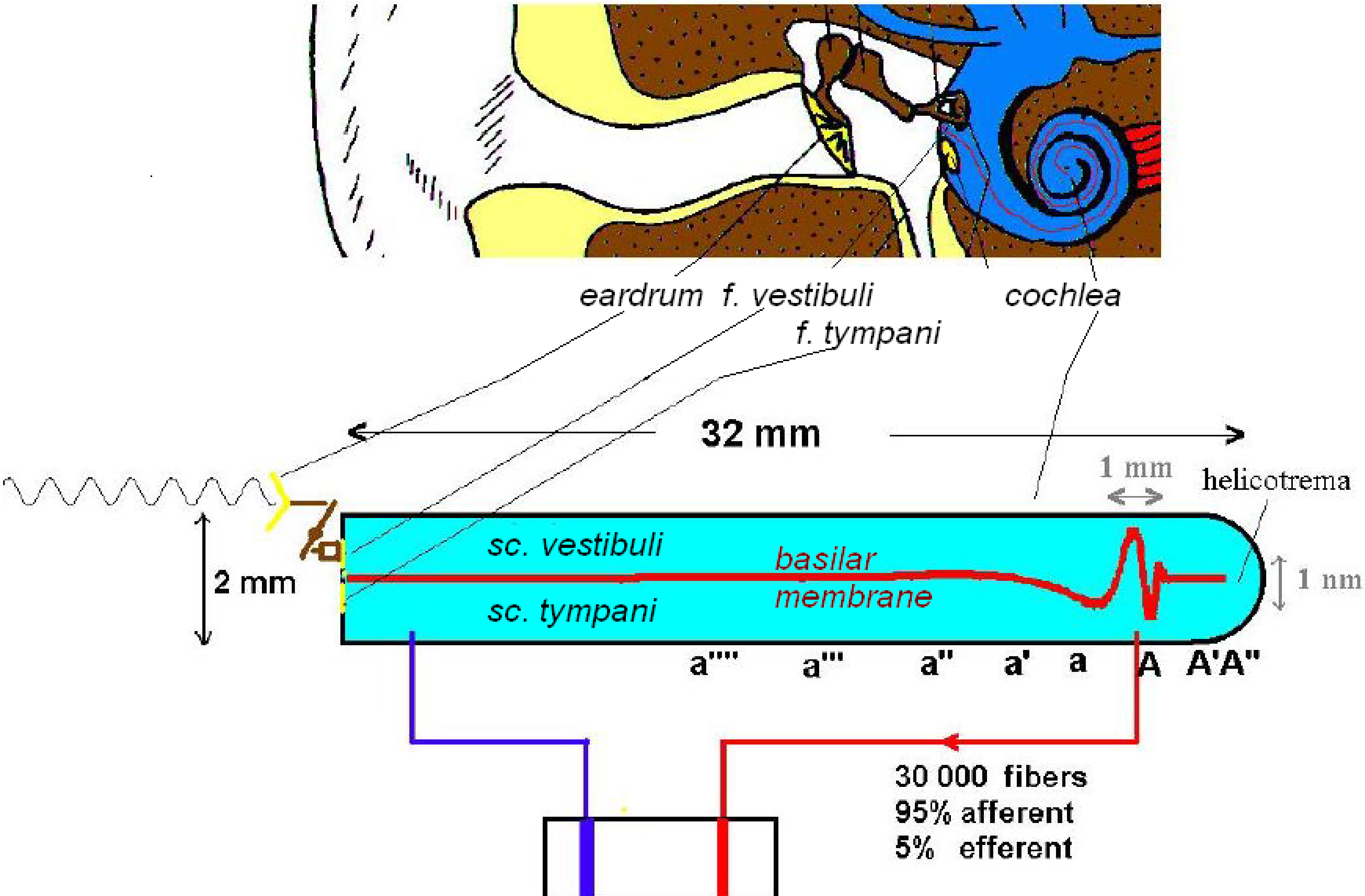
1 Anatomy and Function of the ear




Cochlea
m. tympani
finestra tympani
finestra vestibuli
32 mm
helicotrema
2 mm
1 nm


eardrum
f. vestibuli
f. tympani
cochlea
32 mm
1 mm
helicotrema
2 mm
sc. vestibuli
basilar
membrane
sc. tympani
1 nm
a'''' a''' a'' a' a A A'A''
30 000 fibers
95% afferent
5% efferent


April 21, 1986
THE NEW YORKER
Price $1.50
sempé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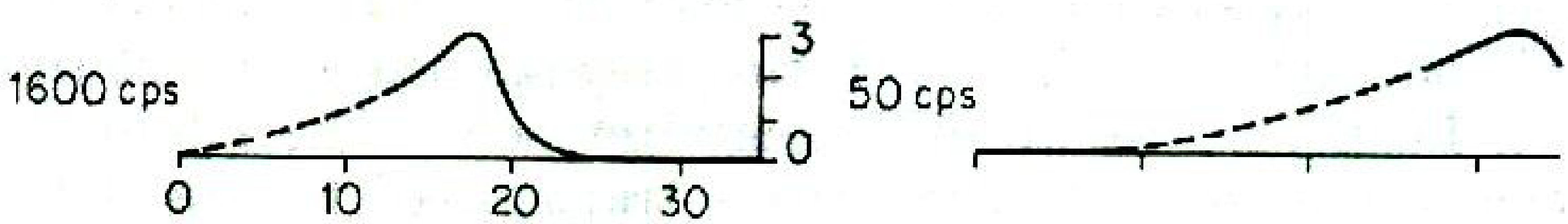
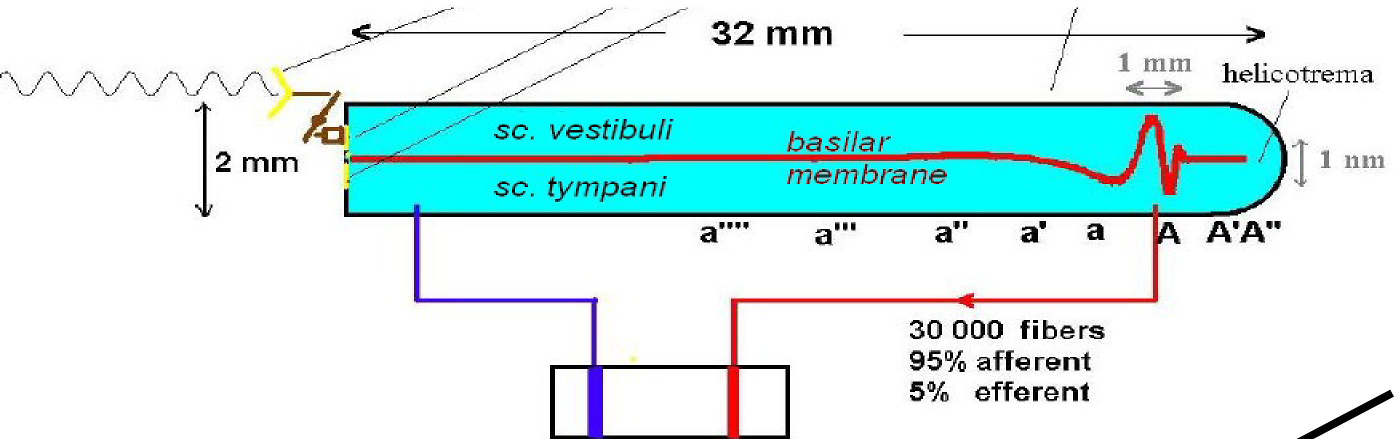
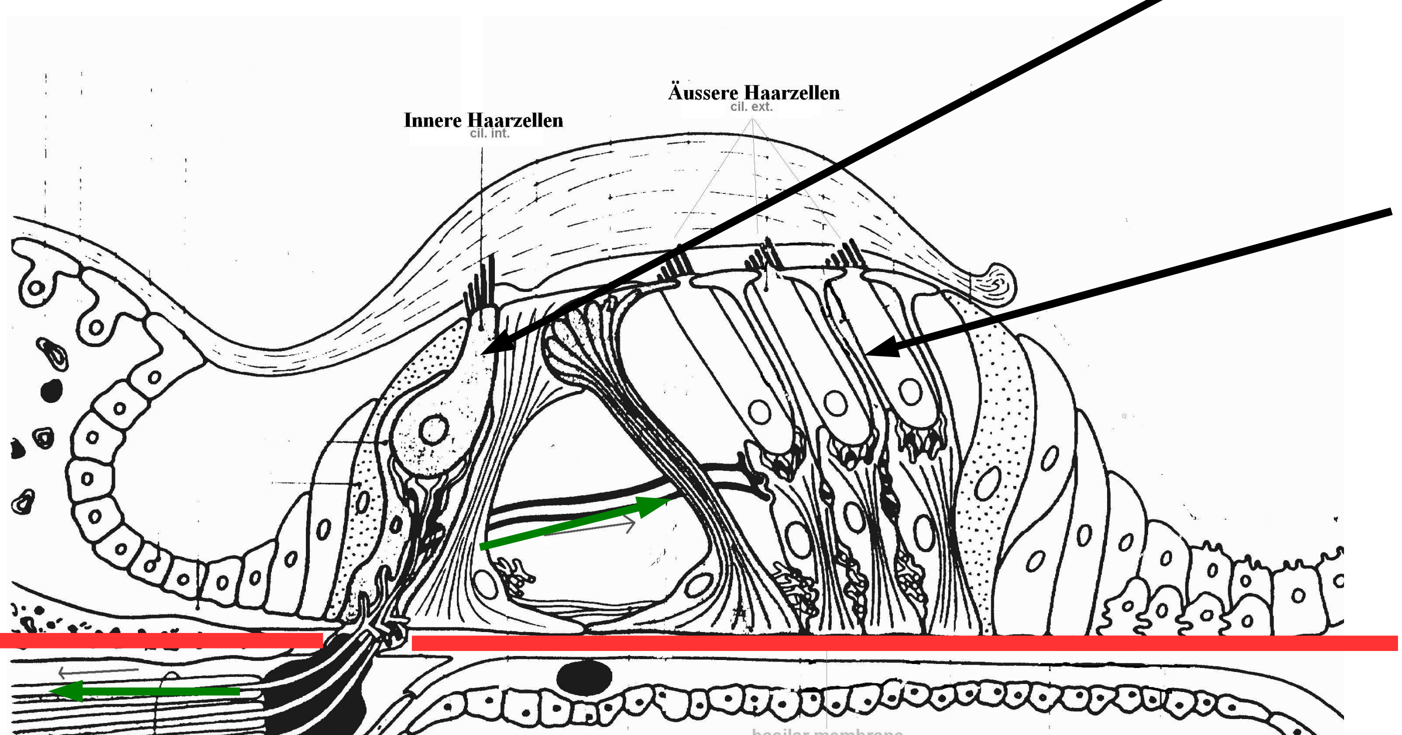
v. Bekesy:


1600 cps
0
10
20
30
3
0
50 cps

The ear is an active organ



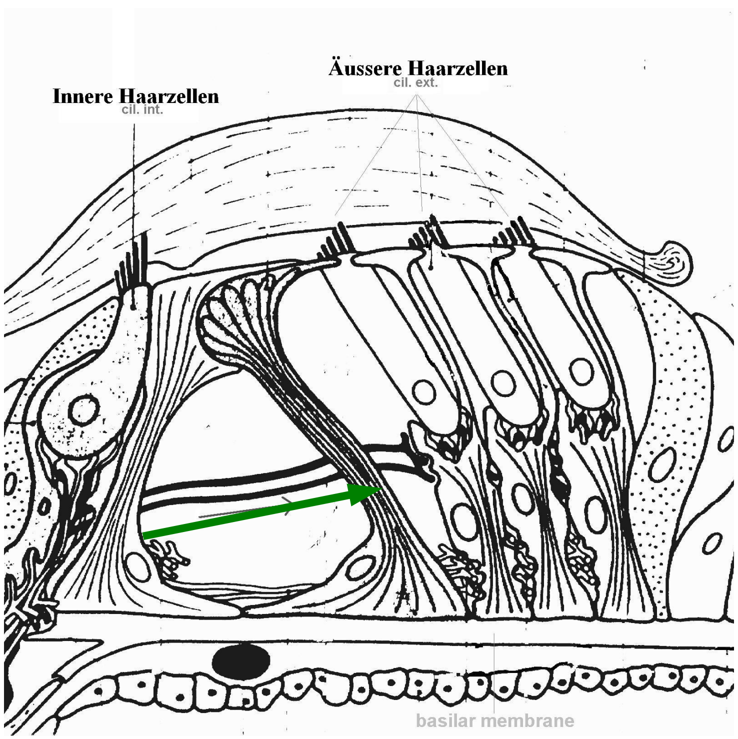


Inner hair cells transform the movement of the bm into electric impulses wich are communicated to the brain through the auditory nerve

Outer hair cells receive signals from the brain and transform it in movement of the b.m.
They ``de-muffle'' the b m and make the width smaller.

basilar membrane

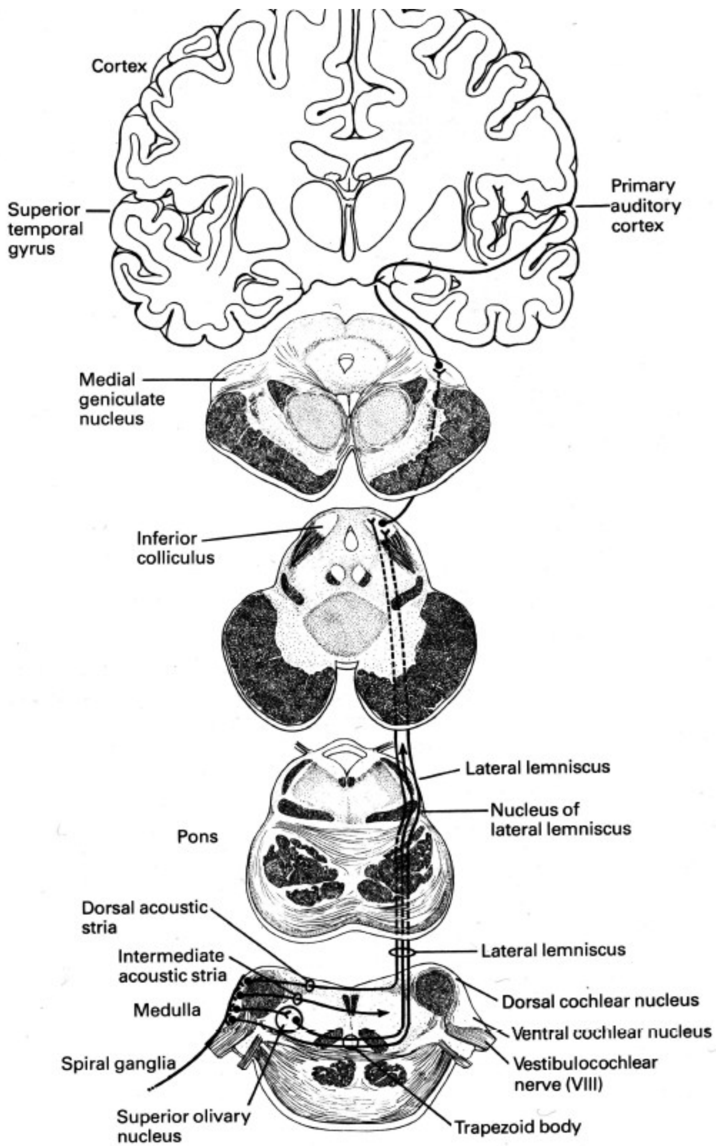
Prof. Jonathan Ashmore - Lab Page
Rock around the clock Hair Cell.
The movie shows a short video of an outer hair cell being stimulated electrically by a patch pipette which enters from the lower left

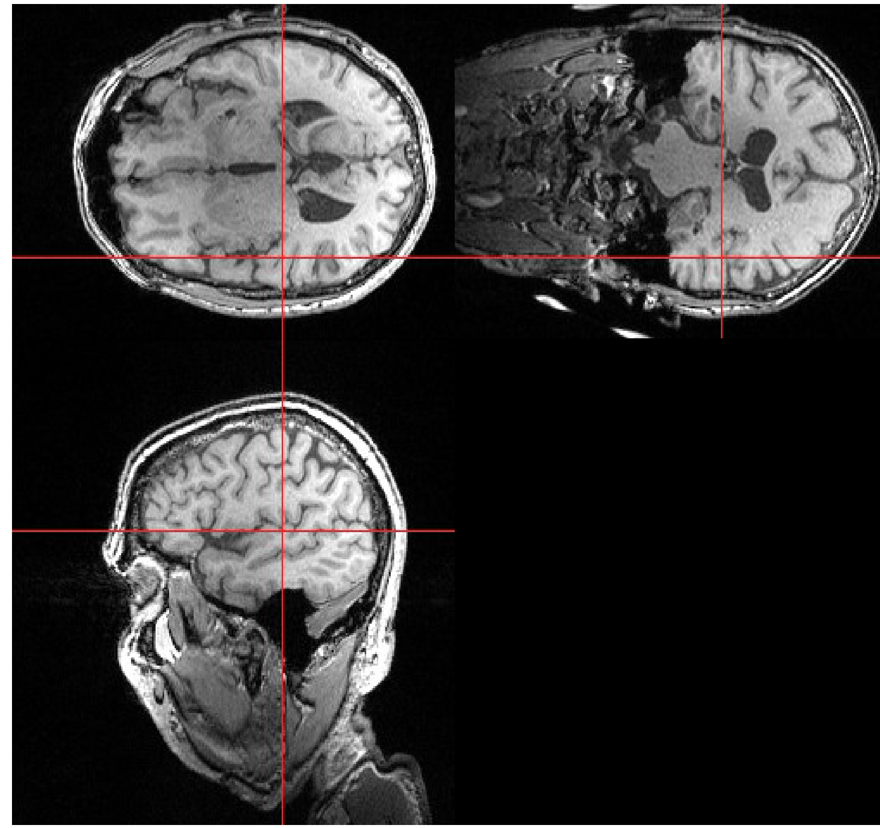


The feedback can be adjusted to the intensity.
In this way the ear manages to be sensitive over an intensity range of 12 orders of magnitude:

hearing threshold:	0.00000000000001	W/mm^2
pain threshold	0.01	W/mm^2
fff	0.00001	W/mm^2
ppp	0.0000000000001	W/mm^2

2 From the Ear to the Brain

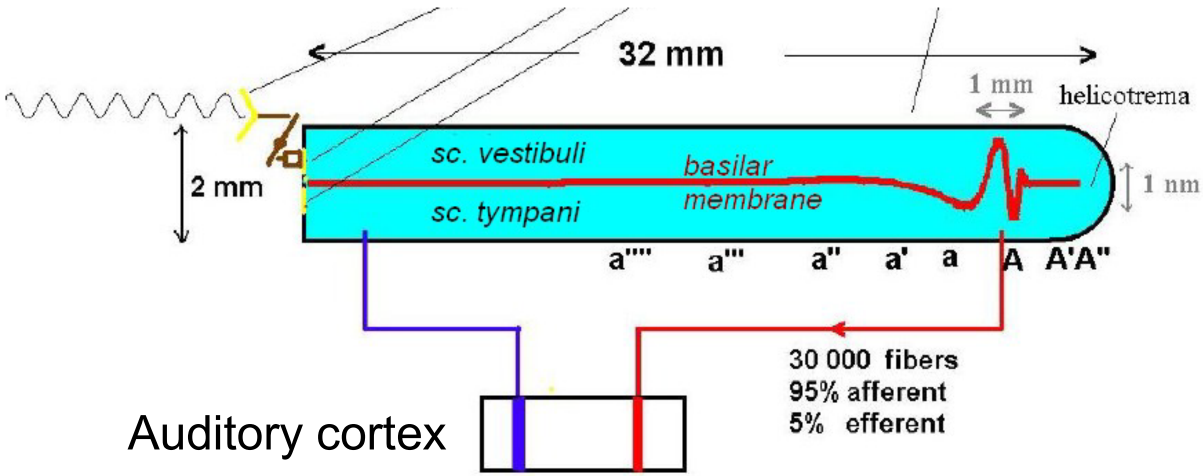


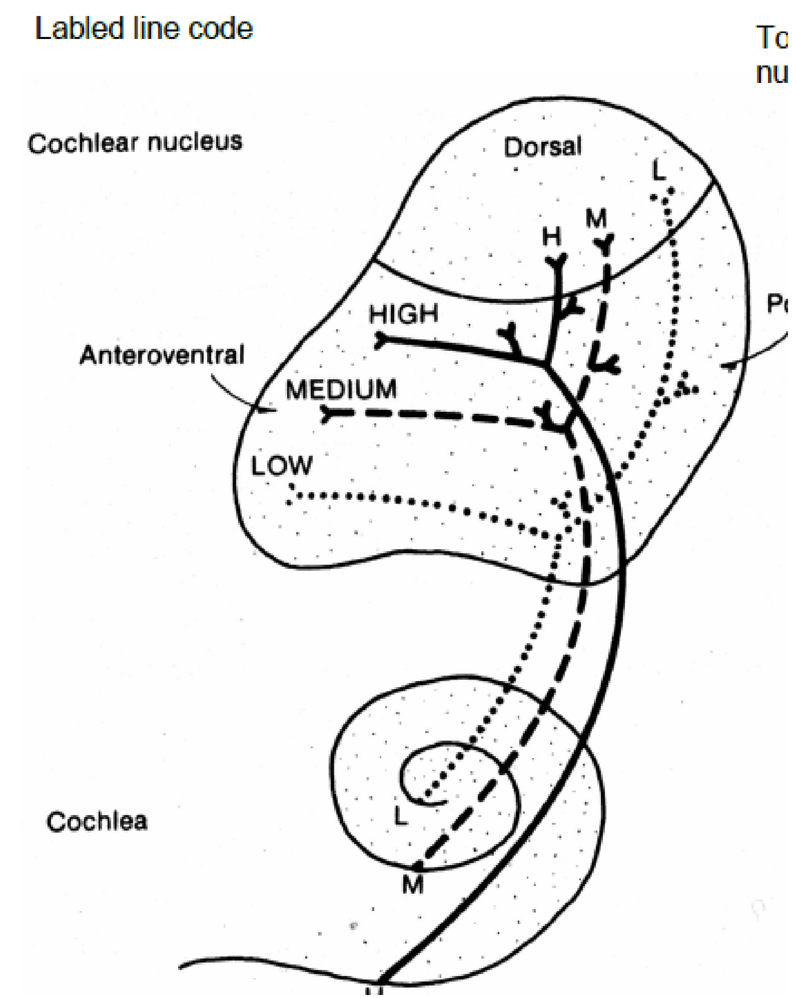


The auditory pathway and its stations from the cochlear nucleus to the auditory cortex.

The information about the sound is transmitted in two ways:

1) Spatial representation: The place, where the b m is excited is communicated to the brain by parallel nerve fibers up to the cortex. This brings the information about the pitch (among other properties)

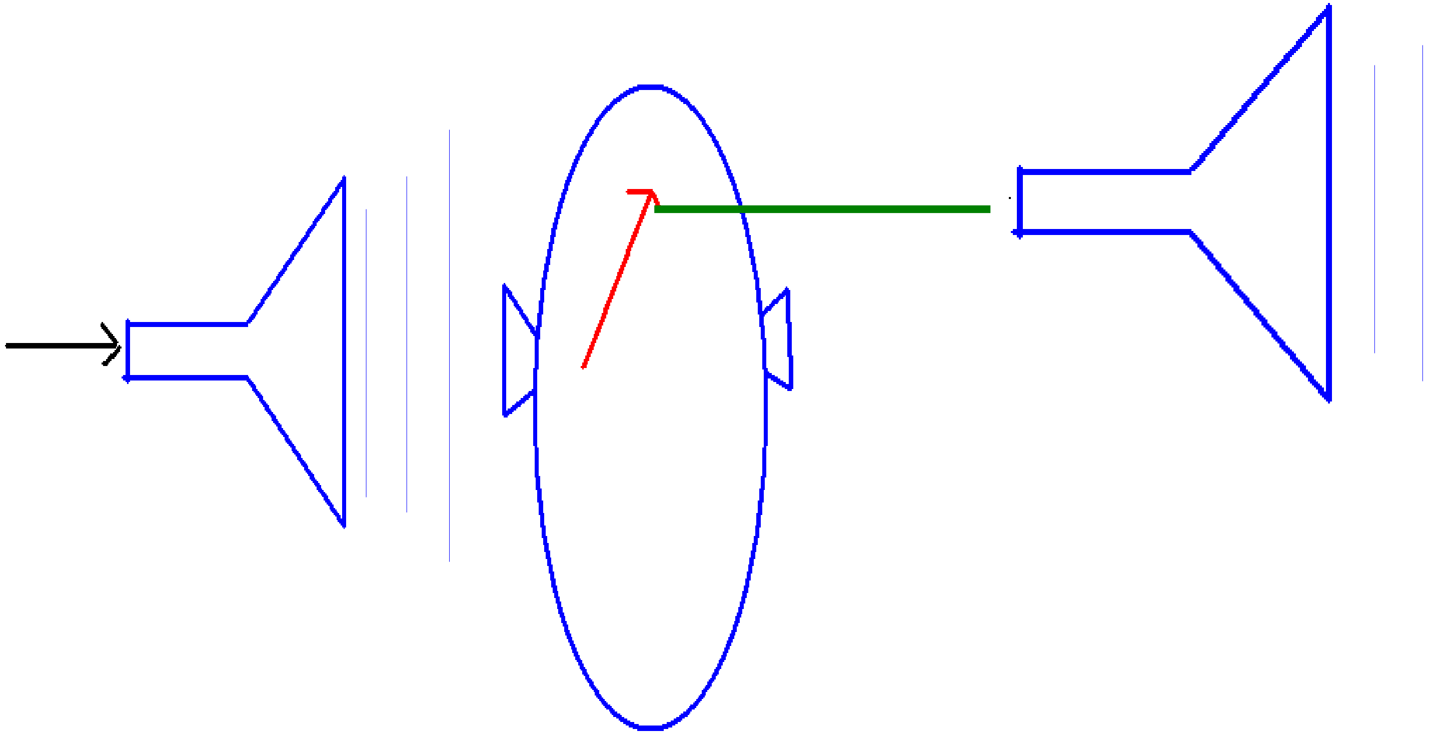




2) Temporal representation

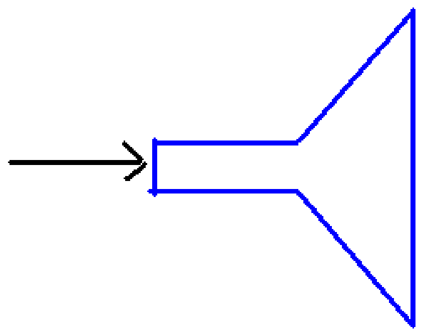
The b m moves with the same frequency as the tone and therefore also the hair celles fire with that frequency (in volleis). Therefore the frequency information is also transmitted in an analog way to the brain.

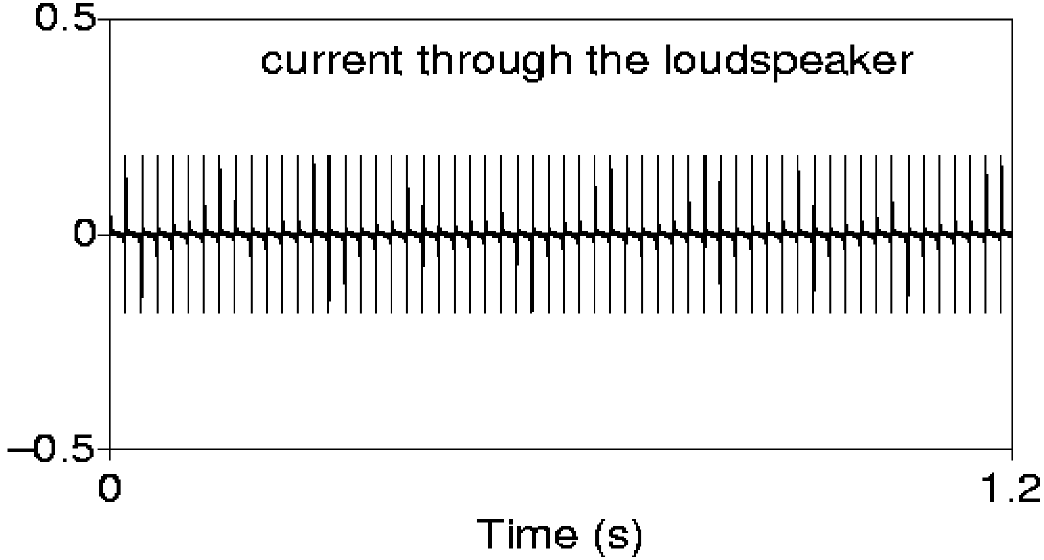
one can hear it:



01-gain_dpe.wav

Sound of the loudspeaker offered to the ear





01-gain_dpe.wav

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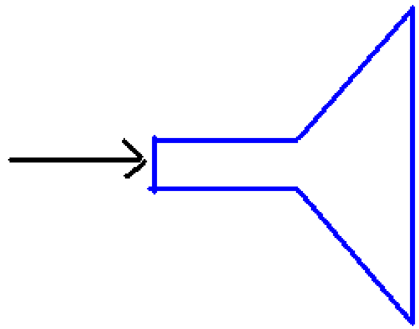
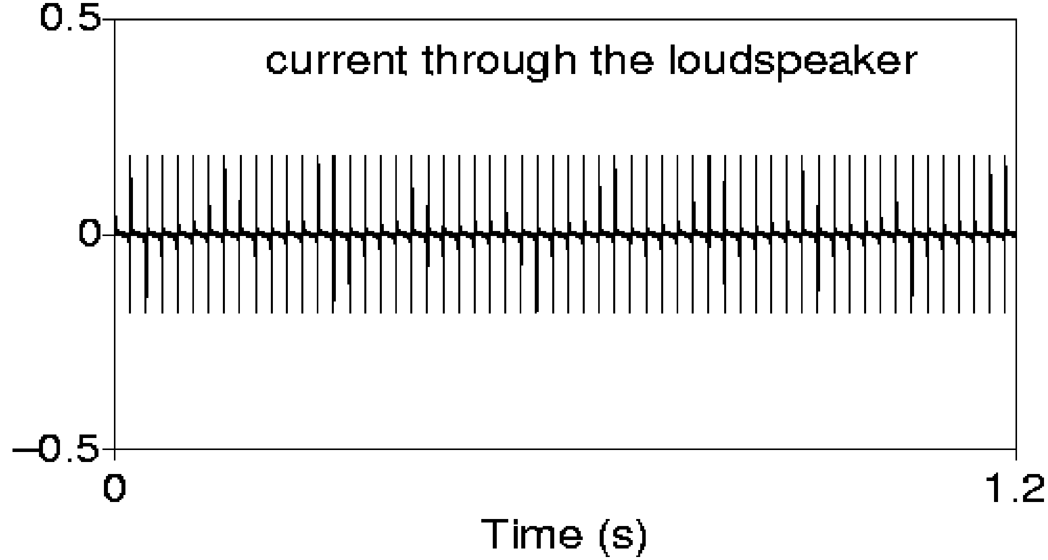
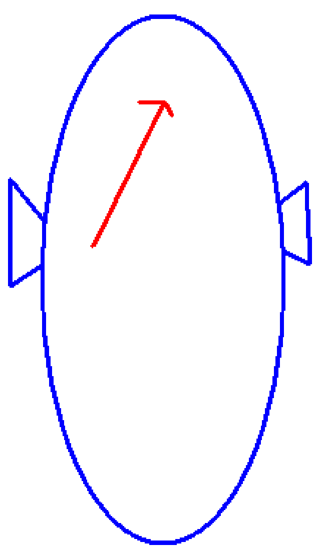
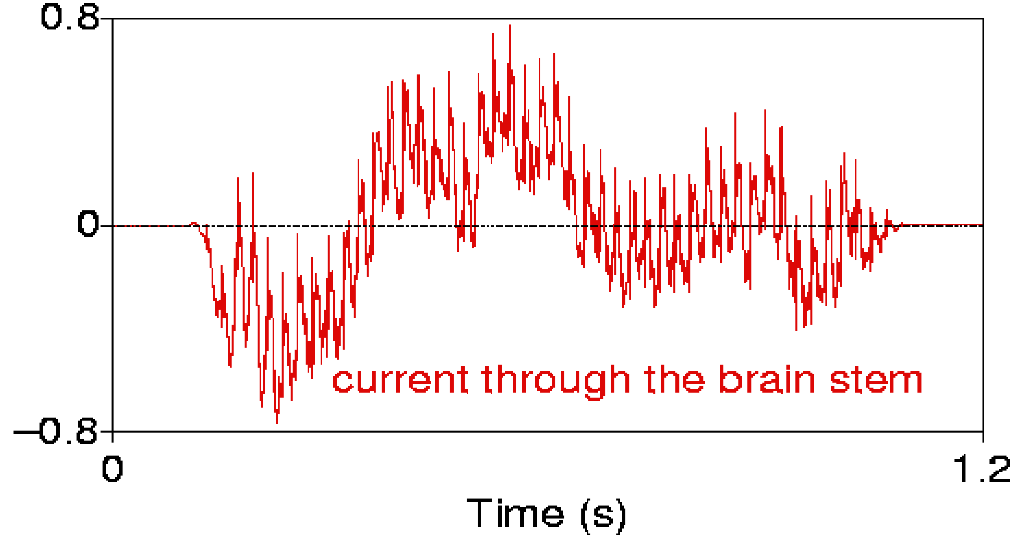




Sound generated by the synaptic currents flowing through the brain stem

dpeffr_02_gain.wav





3) The critical bandwidth and the physiological foundation of dissonance and consonance

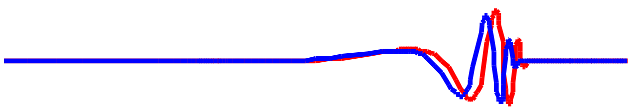
Pythagoras

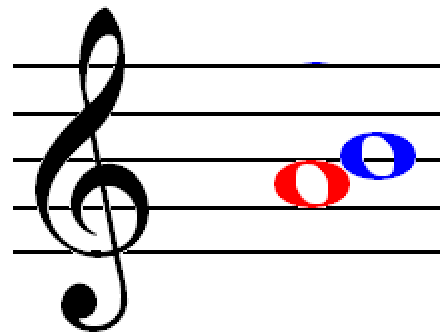
Ohm

Helmholtz

Critical bandwidth: Two tones with different frequency are inside one critical bandwidth, if the main excitation regions on the b m overlap.

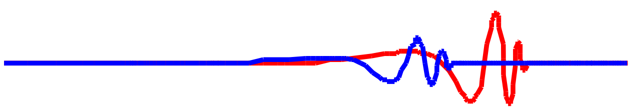
f= 440 and 494 Hz

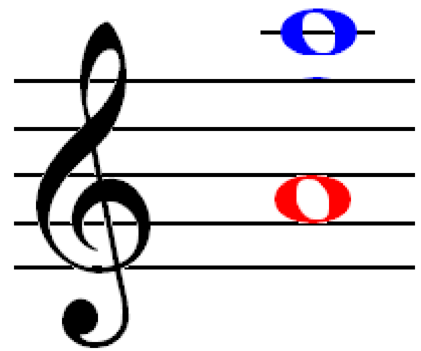


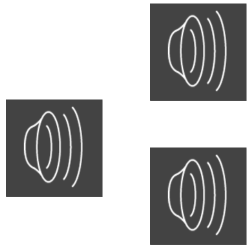


020-a-h 021-a 022-h

f= 440 and 880 Hz





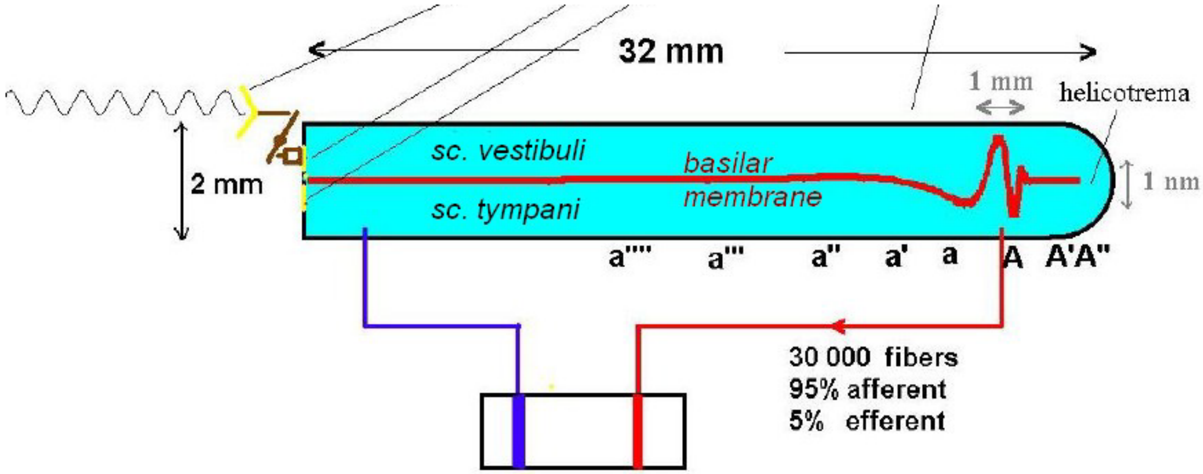


024-a880
023 a-440-880
021-a

Critical bandwidth at 1000 Hz ca 25 % of frequency = ca 1 major third,

ca 1mm on bm

Two tones within one critical bandwidth sound dissonant
Two tones outside one critical bandwidth can be heard separately

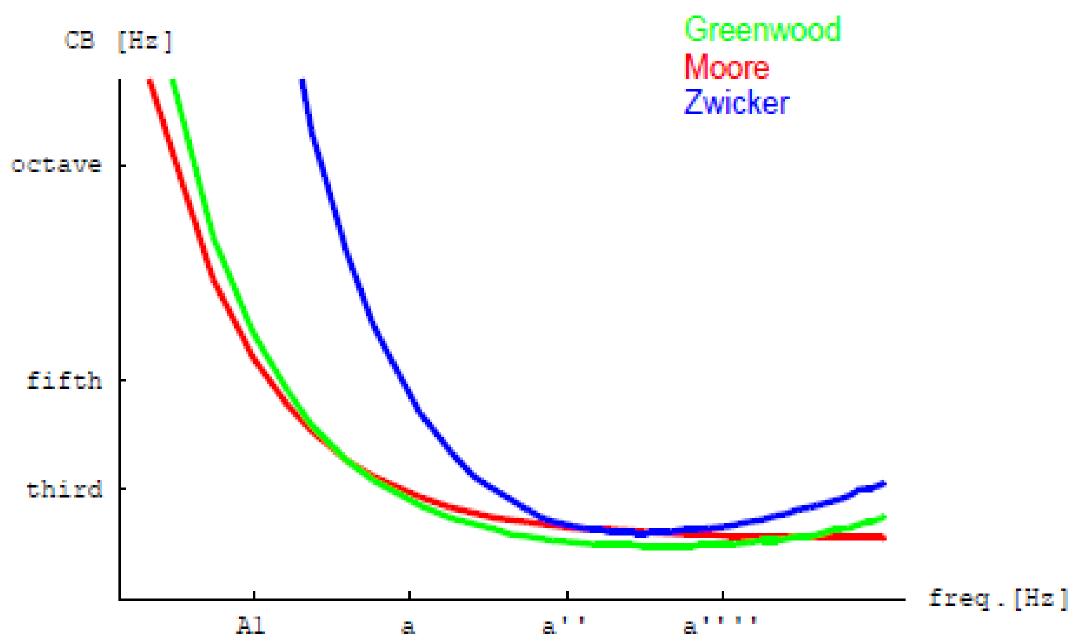


Separation between frequencies decreases for lowering pitch

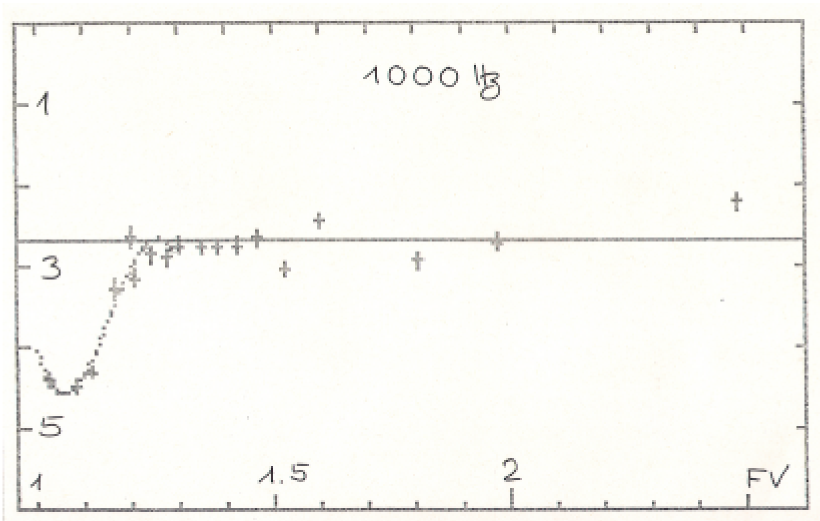
↓

critical band width is larger for low frequencies.

Critical bandwidth in musical notation

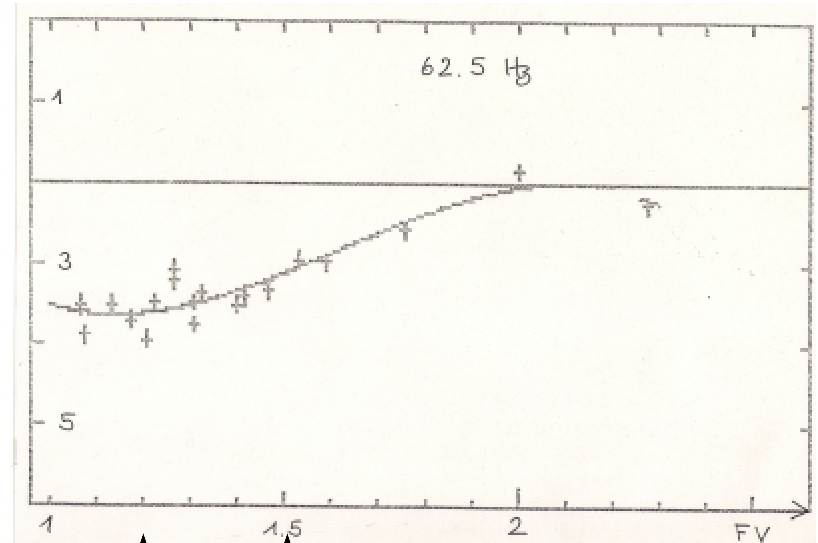


Interval of dissonance



fifth

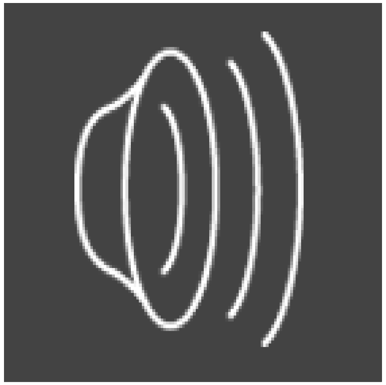
minor third



fifth

minor third

Dosch and Specht, 1986
average of 89 subjects



031-high-fifth.wav

030-low-fifth.wav

Chopin, Prelude

Physiological basis for

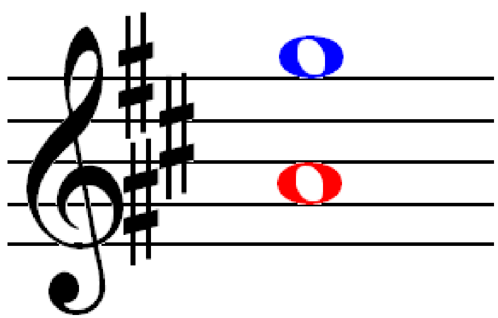
Dissonance of second: Tones overlap on b m

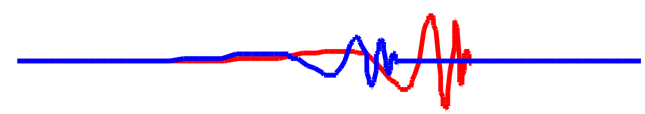
Only octaves in bass : Dissonance interval increases with lower pitch

Any theory of harmony says: The seventh is after the second the most dissonant chord.   Why?

831 Hz

440 Hz





Far apart on the b m

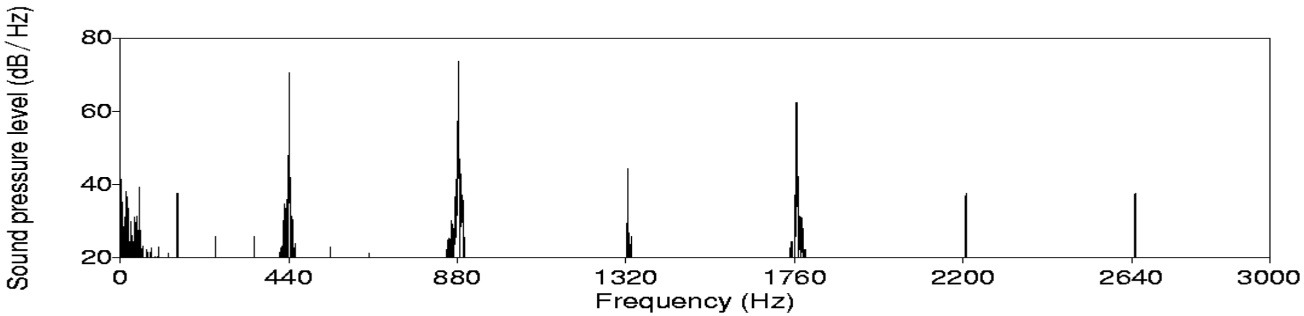
7th

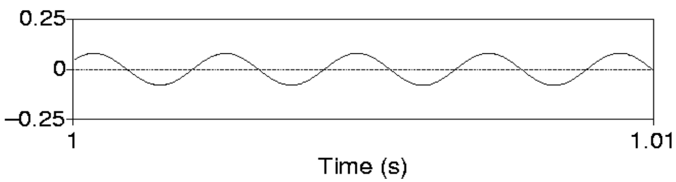
041-seventh-440-831

organ 7th:

042-organ-major-seventh.wav

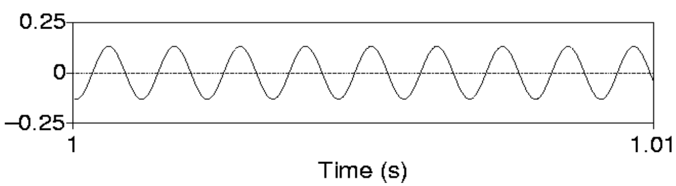
Ohm applied Fourier analysis to periodic processes:
Nearly any tone is in general not a pure tone, but a mixture of many partial tones:





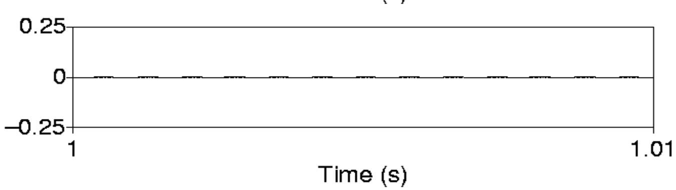
1st partial tone (fundamental)

440



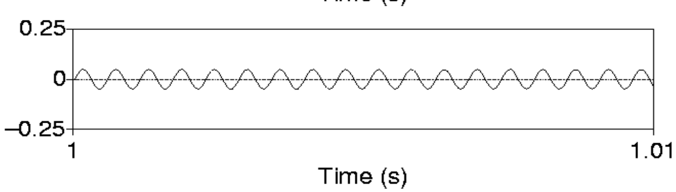
2nd partial tone

880



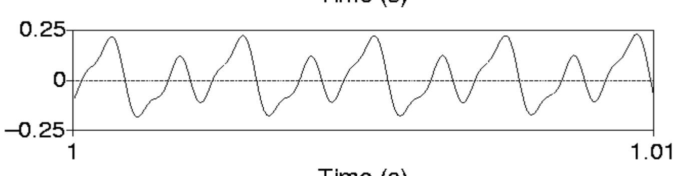
3rd partial tone

1320



4th partial tone

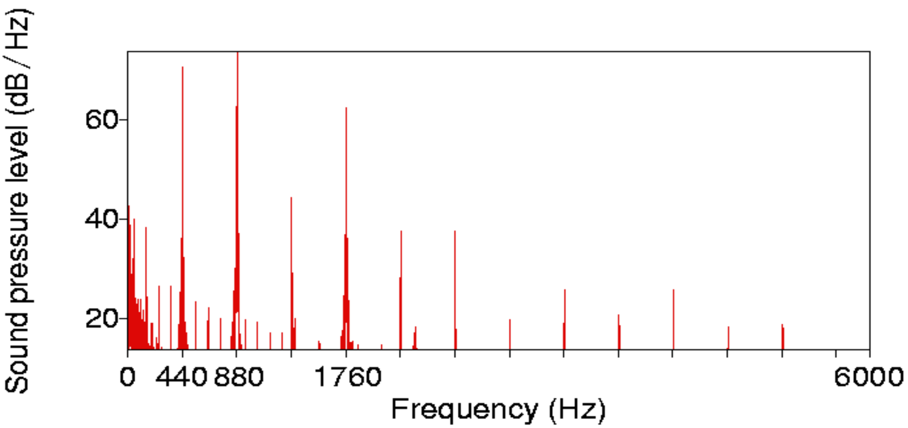
1760

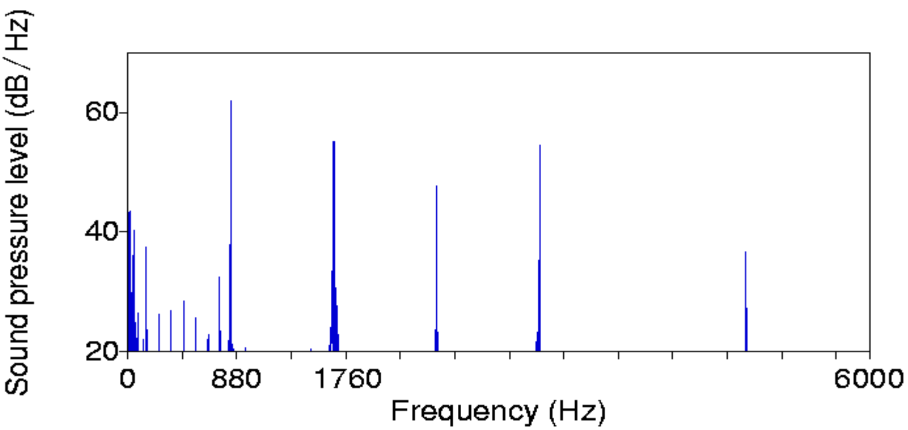


full tone

045-a-synthesis.wav

Helmholtz:



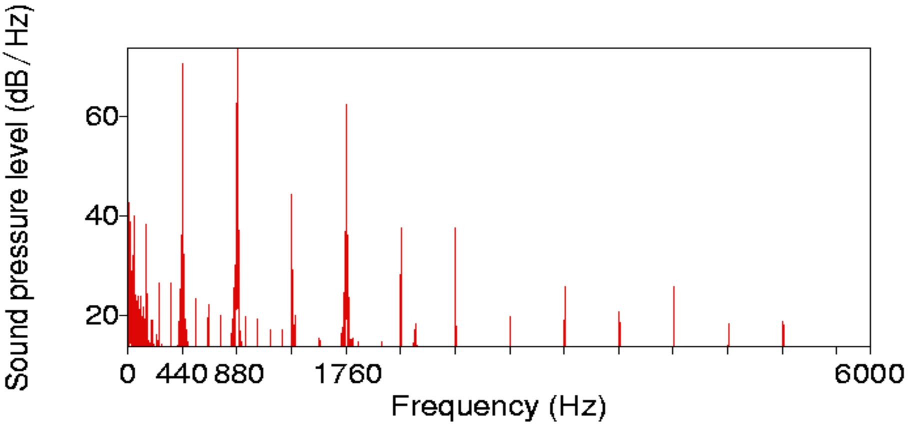


The tone of a musical instrument is in general not a pure tone, but a mixture of many partial tones:
The organ tone a'

has partial tones at
440 Hz, 880 Hz, 1320 Hz , 1760 Hz .....

The organ tone g flat

has partial tones at
830 Hz, 1660 Hz, etc
which are near on the bm the partial tones at
880 Hz, 1760 Hz etc



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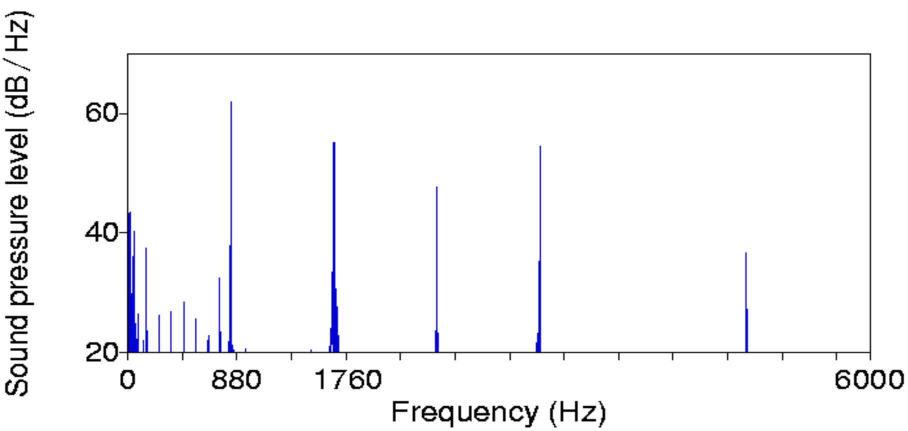

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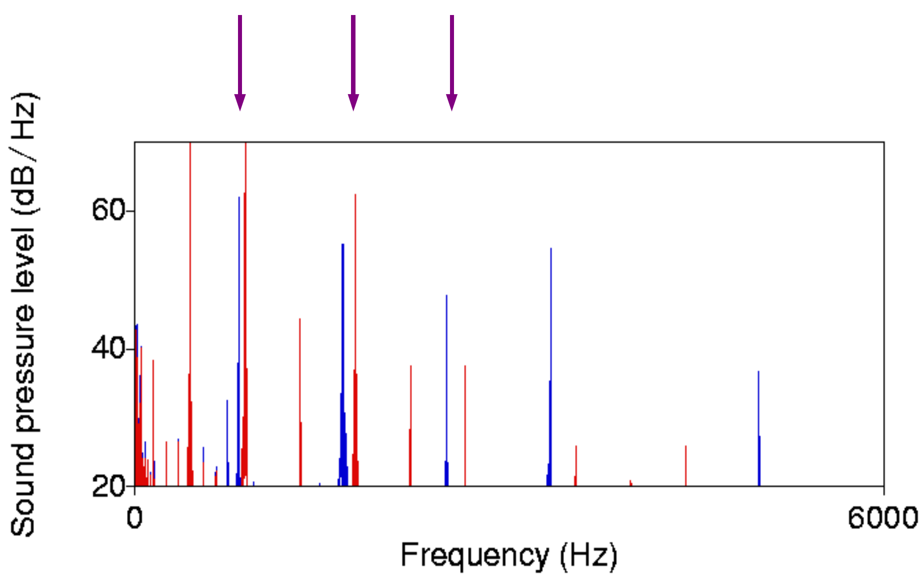
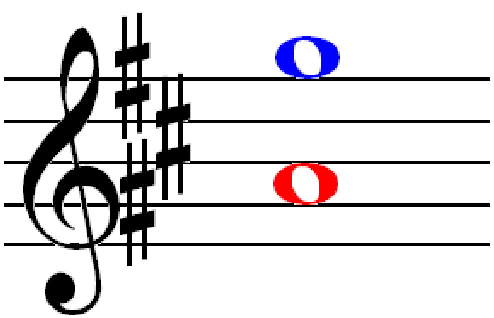




042-organ-major-seventh.wav

For an octave all partial tones have the same frequency:

440 880 1320 1760 2200 2640 3080 3520

880 1760 2640 3520

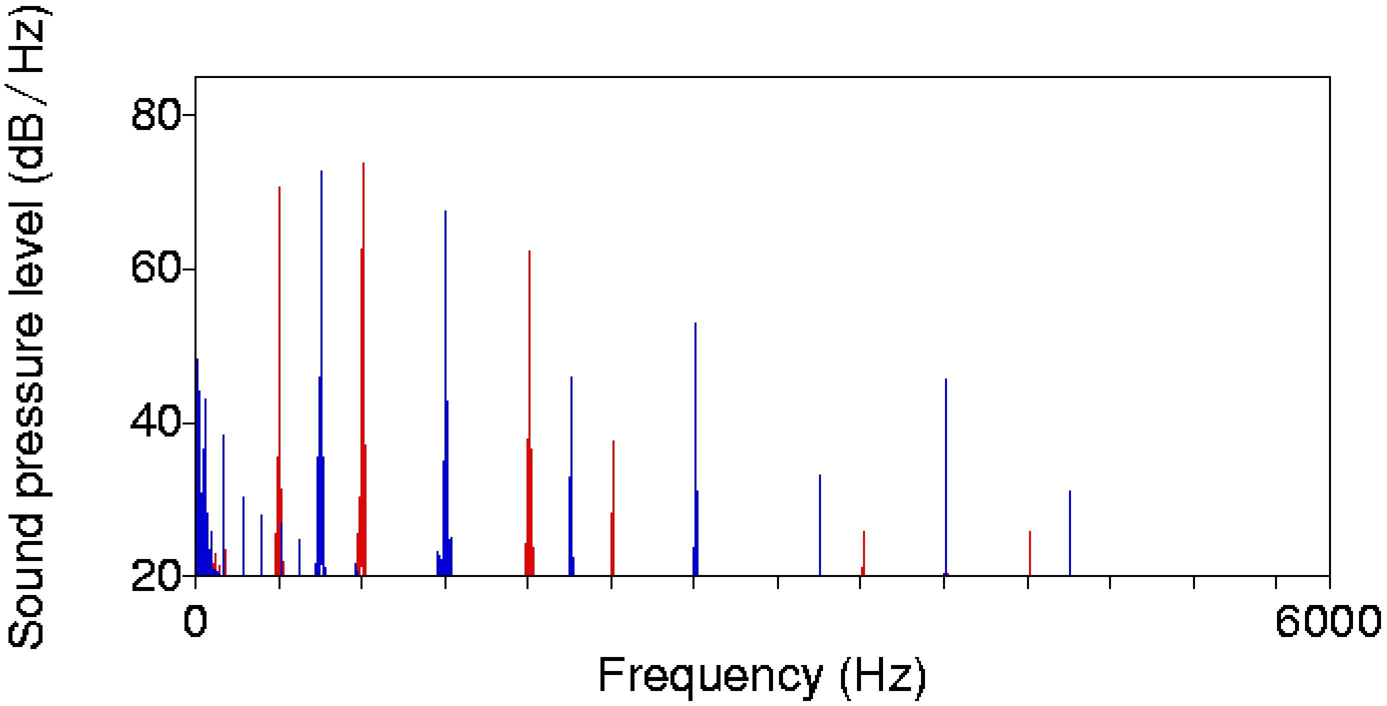
perfect consonance

For a fifth, the partial tones overlap or are outside the critical band width

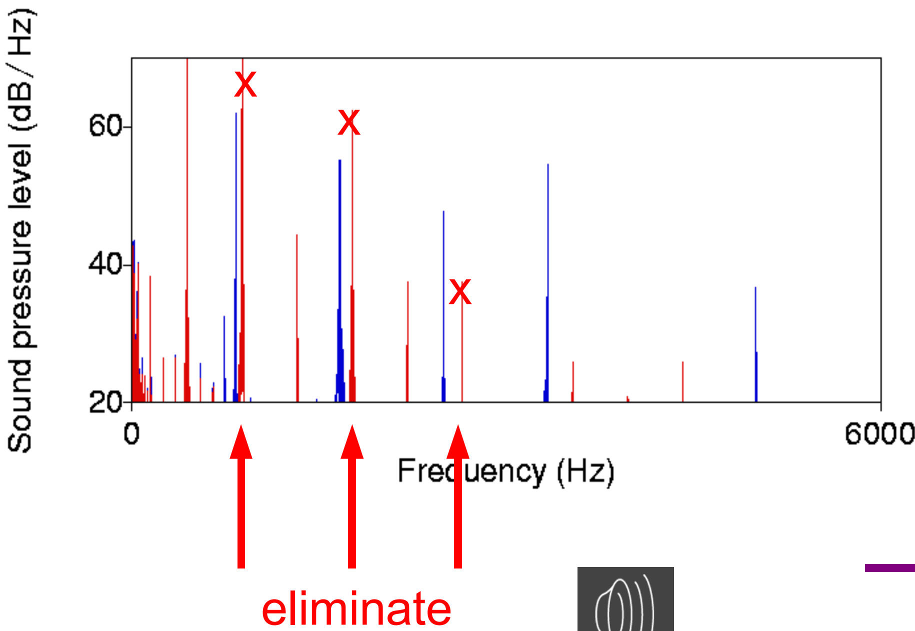
440 880 1320 1760 2200 2640 3080 3520

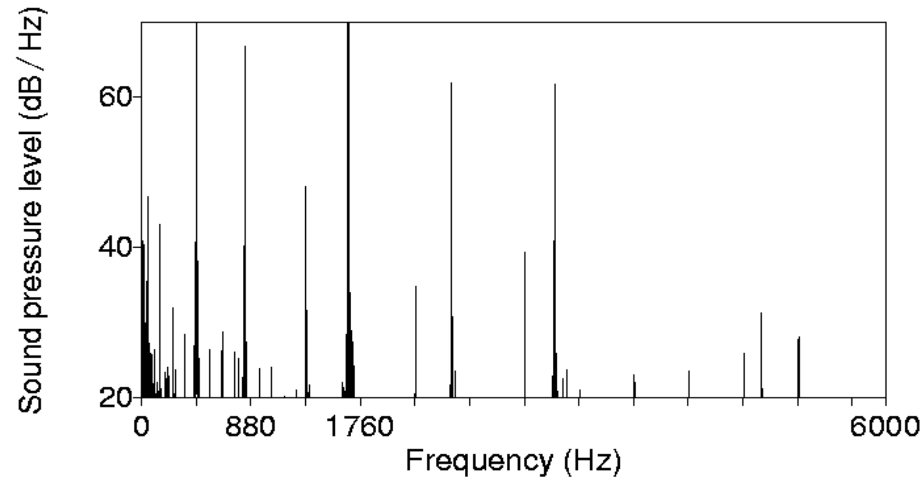
660 1320 1980 2640 3260

next best consonance



Curiosity: one can take out the dissonance from the seventh:



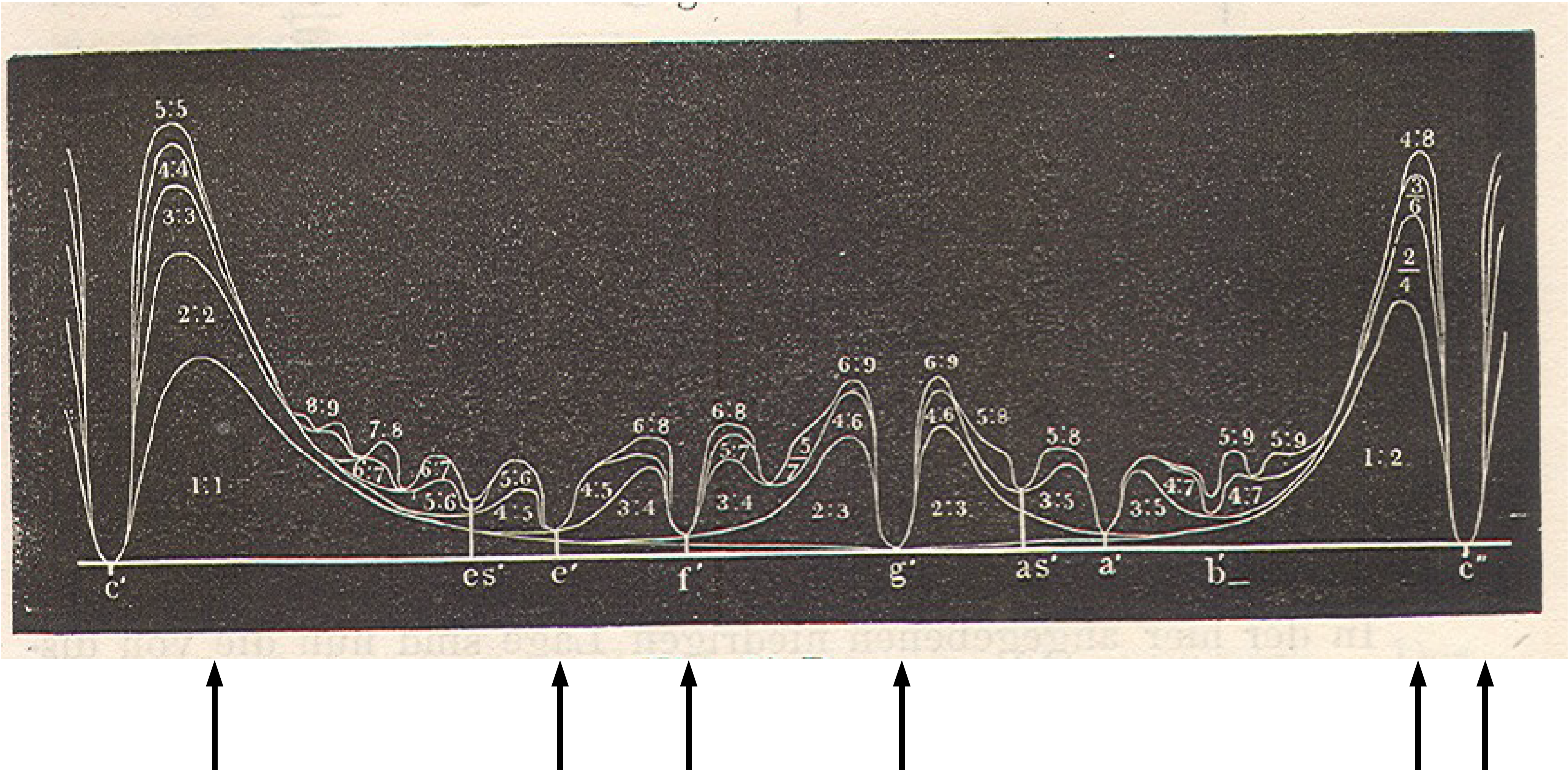


042-organ-major-seventh.wav

043-organ-major-seventh-harm.wav

In contrast: harmonic chords like octave and fifth have no partial tones which are near on the b m

Helmholtz has calculated the degree of dissonance for the different chords



2nd 3rd 4th 5th 7th 8th

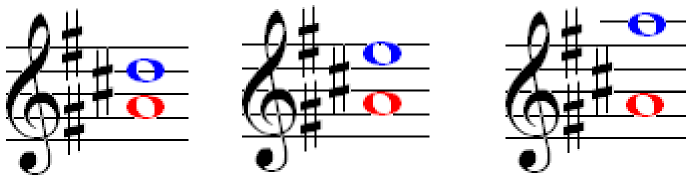
agrees with textbooks of harmony (and historical development)

It explains the ``holy tetrakis'' of the Pythagoreans:

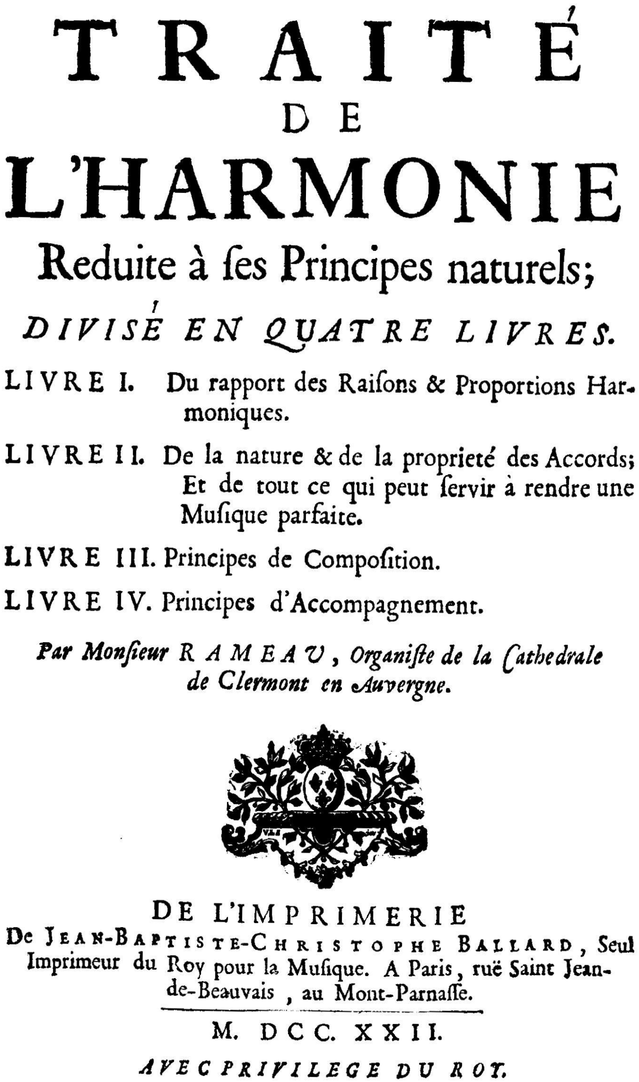
The harmonic intervals are given by the ratios

$$4 : 3 : 2 : 1$$

fourth fifth octave



6) Rameau's theory of harmony
Basse fondamentale



TRAITÉ
DE
L'HARMONIE
Reduite à ſes Principes naturels;
DIVISÉ EN QUATRE LIVRES.

LIVRE I. Du rapport des Raiſons & Proportions Harmoniques.

LIVRE II. De la nature & de la proprieté des Accords; Et de tout ce qui peut ſervir à rendre une Muſique parfaite.

LIVRE III. Principes de Compoſition.

LIVRE IV. Principes d'Accompagnement.

Par Monſieur RAMEAU, *Organiſte de la Cathedrale de Clermont en Auvergne.*

DE L'IMPRIMERIE
De JEAN-BAPTISTE-CHRISTOPHE BALLARD, Seul Imprimeur du Roy pour la Muſique. A Paris, ruë Saint Jean-de-Beauvais, au Mont-Parnaſſe.

M. DCC. XXII.

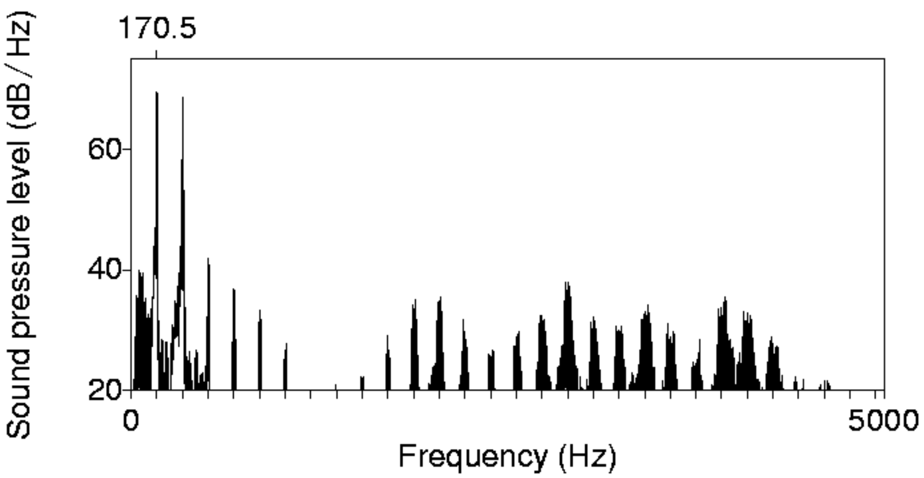
AVEC PRIVILEGE DU ROY.

048-dardanus-example

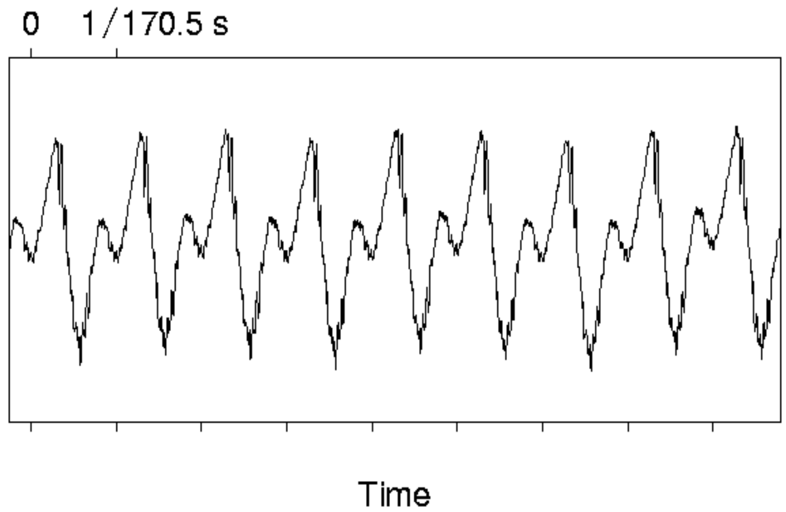
A tone is called harmonic, if the frequencies of the partial tones are all multiples of the same frequency. A harmonic tone is periodic in time

Most musical instruments and the vowels of the human voice are harmonic.

weight of partial tones



time dependence of sound pressure



The partial tones of the spoken vowel a.
The pitch depends on the frequency of the fundamental, the timbre (a, o, e, i....) on the composition of the partials.

Under normal circumstances the different partial tones of a harmonic tone are not perceived separately

Though the tone consists of many partial tones, it is perceived as one tone (fusion of the partial tones) This is specific for harmonic tones.

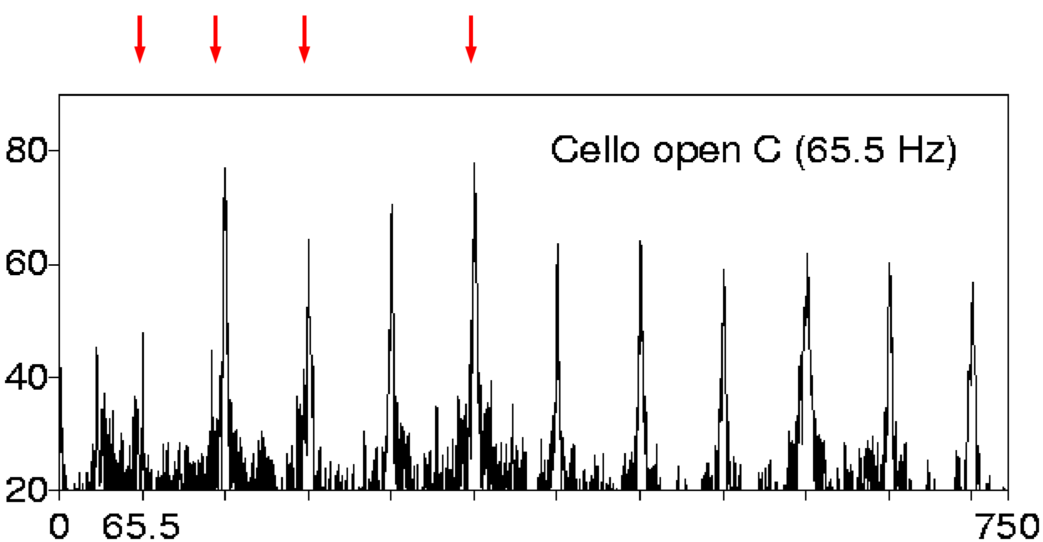
Nevertheless, if one pays attention and has a good musical ear, one can clearly distinct the lower partial tones:

D'Alembert:

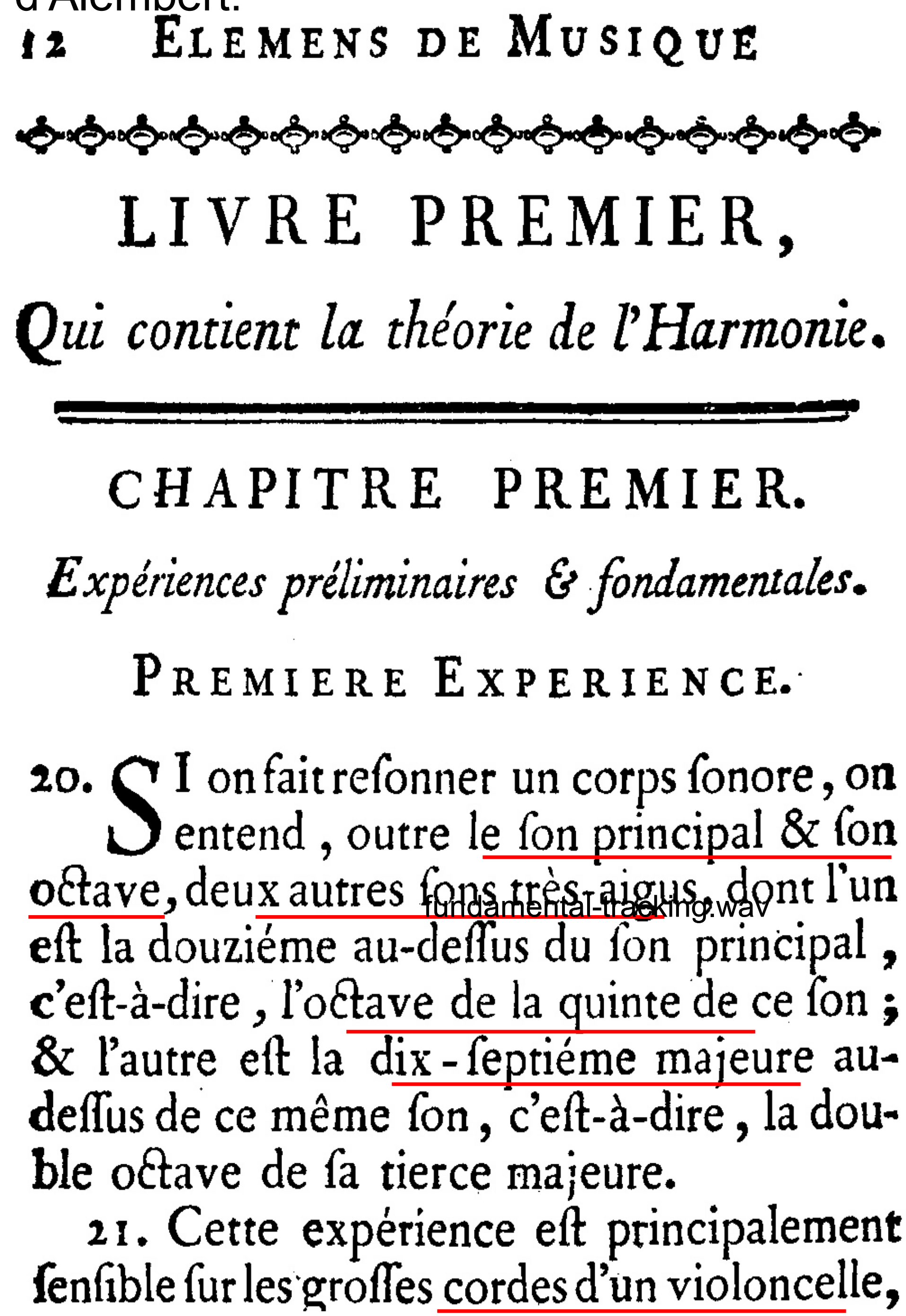
050-Cstringarco.wav

051-Cstringarco-3rdpartial.wav

052-Cstringarco-5th-partial.wav



d'Alembert:



12 ELEMENS DE MUSIQUE

LIVRE PREMIER,

Qui contient la théorie de l'Harmonie.

CHAPITRE PREMIER.

Expériences préliminaires & fondamentales.

PREMIERE EXPERIENCE.

20. SI on fait reſonner un corps ſonore, on entend, outre le ſon principal & ſon octave, deux autres ſons très-aigus, dont l'un eſt la douziéme au-deſſus du ſon principal, c'eſt-à-dire, l'octave de la quinte de ce ſon; & l'autre eſt la dix-ſeptiéme majeure au-deſſus de ce même ſon, c'eſt-à-dire, la double octave de ſa tierce majeure.

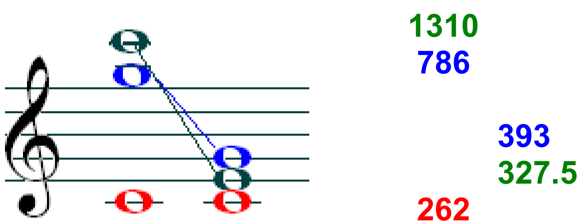
21. Cette expérience eſt principalement ſenſible ſur les groſſes cordes d'un violoncelle,

fundamental-tracking.wav

The occurence of the partial tones in a harmonic tone is the basis of Rameau's theory of harmony:

The major chord consists, **up to octaves,** of the first 5 partial tones of the harmonic tone:

in C : c (do): 1, 2, and 4th partial
e (mi) 4 th partial
g (sol) 3 rd partial



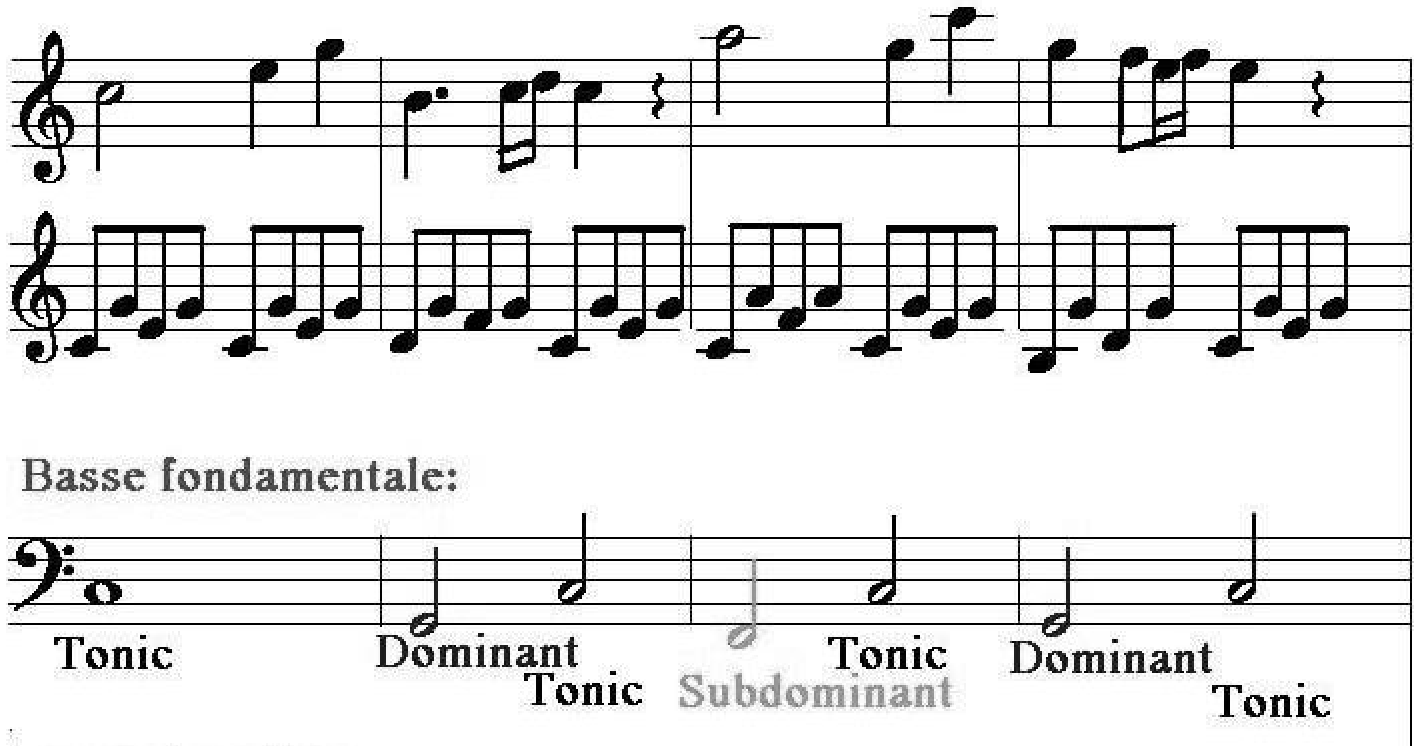
fournissent l'accord le plus parfait
puisque cet accord est l'ouvrage de la nature.
(D'Alembert)

This arangement as partial tones allows to determine to each chord the basis, which is the principal tone: *basse fondamentale* and this *basse fondamentale* is the basis of any chord (Rameau)

Though the c' (do) is the highest tone, it is nevertheless the *basse fondamentale,* since it is the the principal tone in the natural harmonic tone

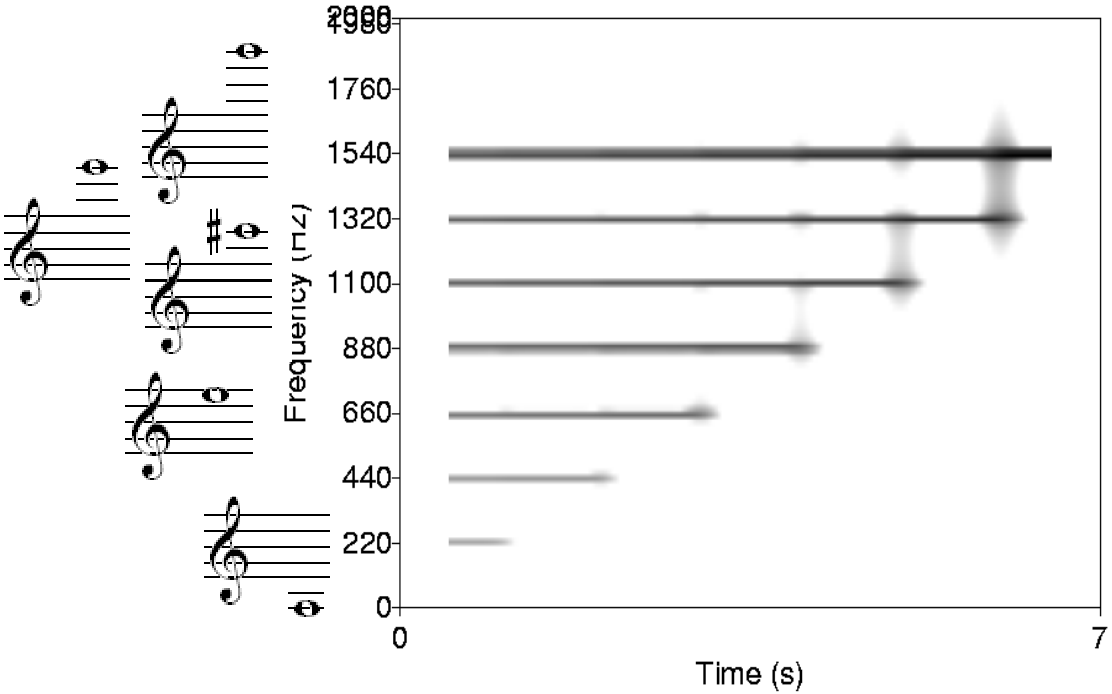
W.A. Mozart, Sonate in C-Dur, KV 545

055-mozart-545



Rameau's *basse fondamentale* (1722) has also a physiological basis:

If we have an incomplete harmonic tone, we hear nevertheless the fundamental tone:



We present a harmonic tone with 7 partial tones. The principal tone is a(220).
If we cut out the principal tone, the two first tone etc, we nevertheless hear the same pitch, that is the tone a(220).
only if 1to 5 is missing, we hear the very high pitch.

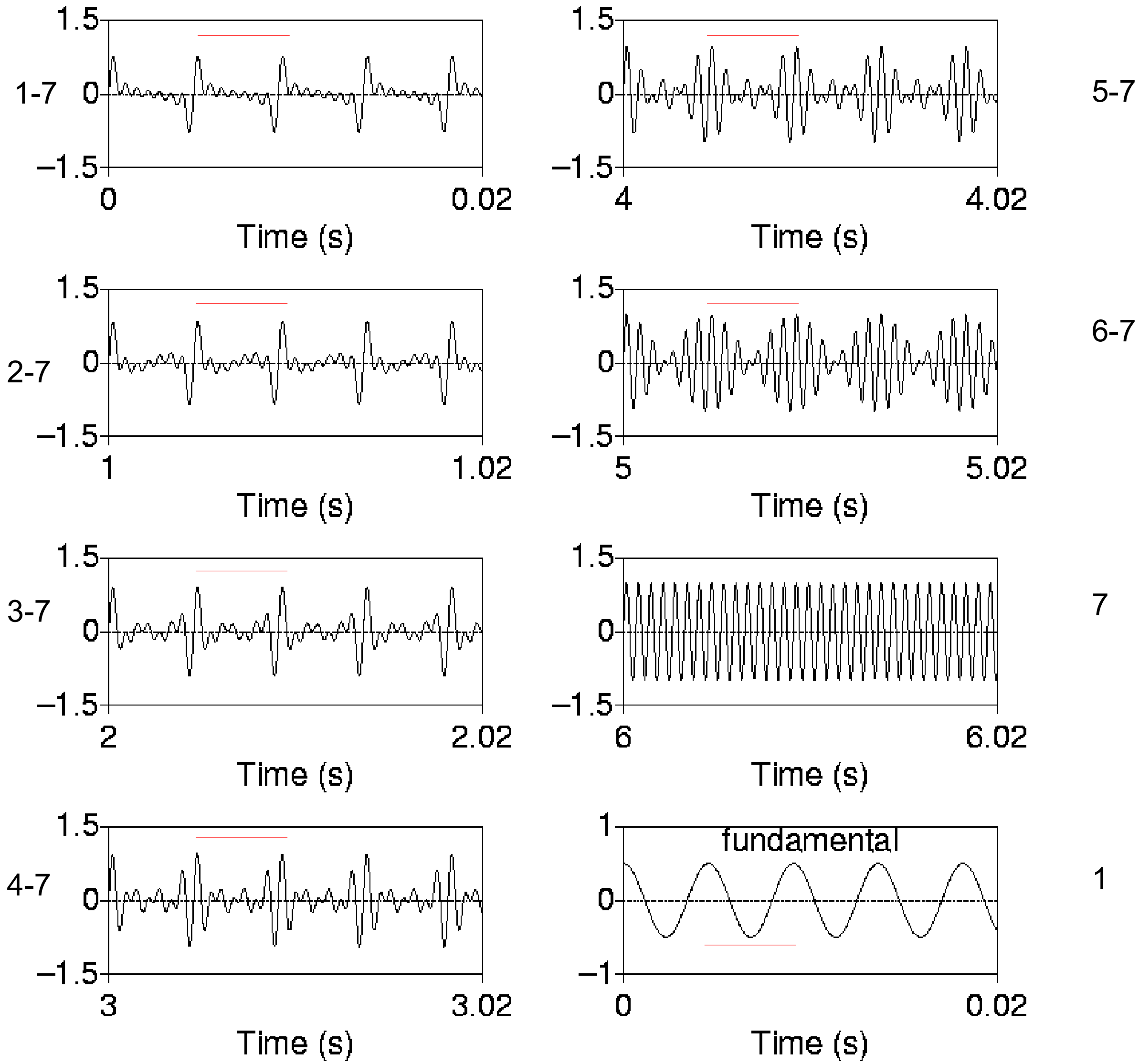
060-fundamental-tracking.wav

061-melodie-1-20.wav

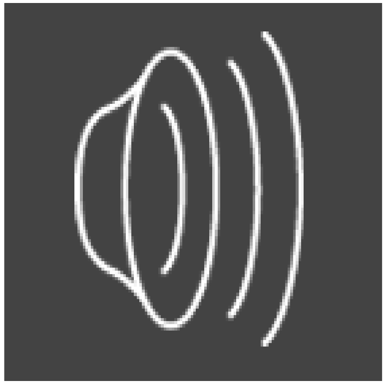
062-melodie-fundamentals.wav

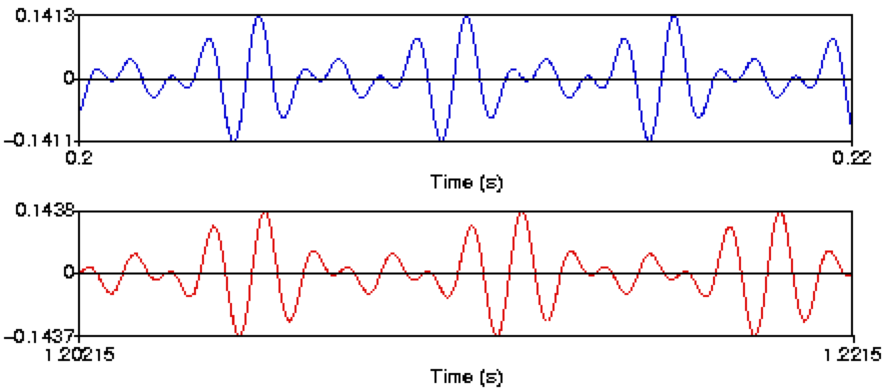
Presumably the temporal coding is important for this tracking of the fundamental tone.

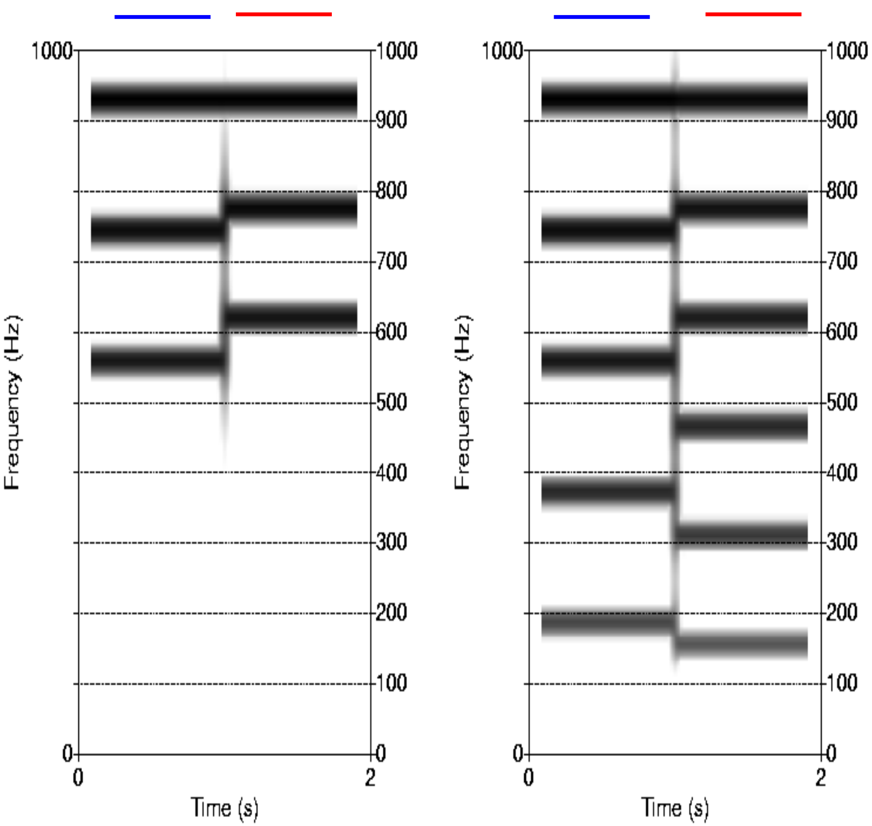
Temporal behaviour (sound pressure of air) of the example. All tones, except the last one (7th partial alone) have the same period as the fundamental tone.

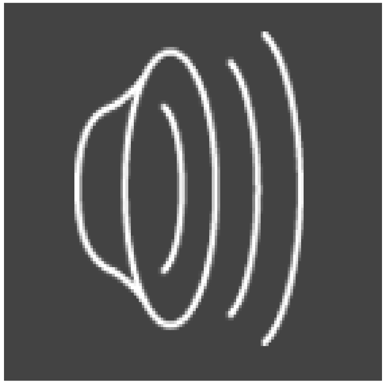


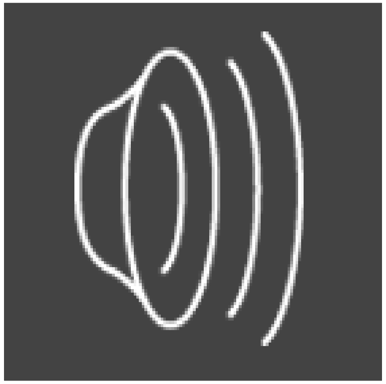
060-fundamental-tracking.wav

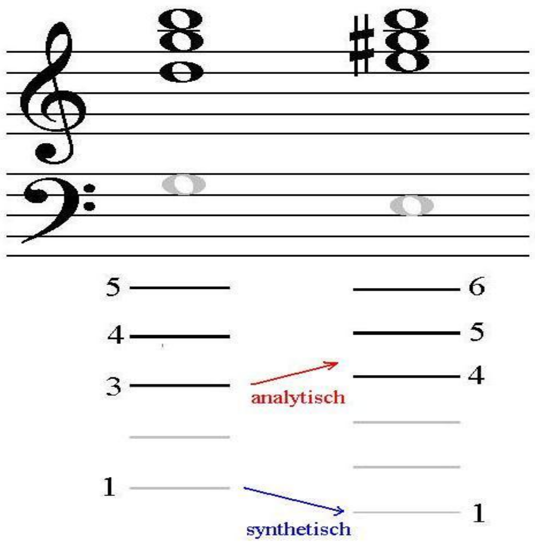



0.1413
0
−0.1411
0.2
0.22
Time (s)
0.1438
0
−0.1437
1.20215
1.2215
Time (s)


1000
900
800
700
600
500
400
300
200
100
0
Frequency (Hz)
Time (s)
0
2
1000
900
800
700
600
500
400
300
200
100
0
Frequency (Hz)
Time (s)
0
2






5
4
3
1
6
5
4
1
analytisch
synthetisch